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Evaluation of the Energy Consumption in MANET

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Abstract: In ad hoc mobile wireless networks, energy consumption is an important issue as most mobile hosts operate on limited battery resource. Existing models for evaluating the energy consumption behavior of a mobile ad hoc network have shown that the various components of energy related costs include transmission power as well as power of reception.

In this paper, we extend the model for calculating the energy spent at a node due to a flow in the network. We include the transmission and reception costs if the node belongs to a flow, and reception costs if it is near a flow. The model gives the energy costs of nodes in ideal conditions where interferences and collisions are absent, and hence can be extended to evaluate the effect of interference between flows on energy consumption in more realistic conditions. The collisions due to the flows are also measured, which are used to evaluate the effect of such interference in the energy consumption. We then show how the extra energy spent due to collisions can be calculated by predicting the collisions in the nodes of the network. This prediction is shown to be capable of accurate calculation of the extra energy consumption.

Key-words: Ad-hoc networks, energy, interferences, IEEE 802.11b, collisions.

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Evaluation de la consommation d'énergie dans MANET

Résumé : Dans les réseaux sans fil et mobiles, MANET, la consommation d'énergie est un aspect important parce que la plupart des terminaux mobiles opèrent sur des batteries dont la capacité est limitée. Des modèles existants d'évaluation de la consommation dénergie dans MANET ont montré que l'énergie est dépensée aussi bien en émissions qu'en réceptions des paquets.

Dans ce rapport, nous étendons le modèle de calcul d'énergie consommée par un flux sur un noeud du réseau. Lorsque le noeud est visité par le flux, le calcul inclut l'énergie consommée en émission et en réception. Ce modèle permet d'évaluer la consommation d'énergie dans un cas idéal: c'est-à-dire en l'absence d'interférences et de collisions entre les flux du réseau. Nous montrons ensuite comment étendre ce modèle pour prendre en compte les interférences et obtenir un modèle plus réaliste. Les collisions entre flux sont considérées et nous quantifions la quantité d'énergie supplémentaire due à ces collisions.

Mots-clés : Réseaux ad-hoc, énergie, interférences, IEEE 802.11b, collisions.

Contents

1 Introduction

A Mobile Ad hoc Network (MANET) is a decentralized infrastructure-less network where wireless nodes move arbitrarily. The node communicate directly to nodes in transmission range, and take part in multi-hop communication with others. Such networks are gaining more and more popularity because of their ease of deployment. However, they are subject to more challenges than conventional wireless and wired networks. Due to the shared wireless medium and its dynamic nature, such networks face various problems like unpredictable topology, increased interference and congestion, and limitation of resources like bandwidth and energy.

The nodes in this type of networks are usually power constrained since they depend on limited battery resources while wireless communications consume lot of energy. Wireless also means that there is a shared environment, and some energy is consumed due to neighborhood transmissions: nodes are spending their batteries not only by sending their own packets, but also by just overhearing packets from other nodes. As ad hoc network is based on multi-hop communication, energy is also spent by forwarding packets for others. The uniqueness of this decentralized network requires different energy management strategies. Design of ad hoc networks while considering the energy issues has spurred a great deal of research interest recently.

Feeney et al. [4, 3] have presented an energy consumption model in terms of the costs of both sending and receiving traffic. The results presented have become a basis of comparing the behavior of routing protocol considering the overhead due to routing as well as the data traffic. In this paper, we extend this model by calculating the energy consumed at each node due to flows in the network. We consider not only the transmission and reception costs of the nodes belonging to a flow, but also the costs due to interference of the flows in these nodes and other nodes in the neighborhood of the flows. By simulation, we show the accurateness of the model, then use this model to evaluate the effect of interference and collisions on the energy consumption.

The remainder of this paper is organized as follows. In section 2, we outline various energy management techniques and the energy measurement model presented by Feeney. In section 3, we present our model for calculating the energy costs at various nodes. Section 4 describes the simulation methodology, and section 5 presents the results and their discussion. A method for predicting collision and measuring the energy consumption due to collisions is discussed in section 6. Finally, we conclude in section 7.

2 State of the art and motivation

2.1 Power consumption model and characteristic of MANET

The wireless channel is characterized by signal strength attenuating with distance from the transmitter. The commonly used power-attenuation model for the decay of the signal is represented by the non-linear formula

$$P_R(d) = \frac{P_T}{d^\alpha} \tag{1}$$

where P_T is the transmitted signal strength, d is the distance from the transmitter, $P_R(d)$ is the amplitude of the received signal at distance d, and α is the path loss factor whose value is typically between 2 and 6. Nodes can correctly receive a packet if the signal strength of the packet at that node is above a certain threshold called Receive Threshold. If the distance between the transmitter and receiver is such that the signal strength is above this threshold, the receiver is said to be within the transmission range of the sender. There is a lower threshold called Carrier Sense Threshold, up to which the received signal strength is enough for the receiver to detect the packet sent, but the receiver is unable to receive it correctly. All received signals that fall between these thresholds cause the channel to be sensed busy and contribute to the interference at the receiver.

Another important parameter in wireless network is the Signal to Interference Ratio (SIR). This parameter gives the ratio of the received signal strength to that of the co-channel and adjacent channel interference. If the current SIR is lower than the SIR threshold β (typically of 10dB in 802.11 networks), even though the received signal strength is above the required Receive Threshold, it cannot be received correctly, as the interference signal is too high. In such a case, collision is said to have occurred, and the packet is lost. Increasing the power of transmission can increase the received signal strength, which could increase SIR, but it can also increase the interference for other nodes. In this paper, we will only consider omni-directional antenna, i.e., any other nodes within the wireless range of a node can be interfered by the node's signal, thus increasing the chances of interference.

2.2 Energy-aware routing protocols

The mobile nodes in MANET usually need to be untethered, and thus powered by batteries which provide limited energy. In the absence of central controlling entity like a base station, each node have to participate in distributed protocol(s) for building routes, causing them to spend more energy. In the past few years, many energy-aware protocols have been proposed for wireless MANET and sensor networks. They are aiming at solving different goals as described below.

The first set of protocols try to minimize broadcast traffic, and the energy thus spent. BIP [21], LMST [8], and [14] are based on minimum-energy broadcasting using Minimum Spanning Tree development. Similarly, [19] uses Shortest-Path Tree development. There has also been some work done on the formation of a virtual backbone, like Connected Dominating Sets and other forms of clustering algorithms for routing purposes, e.g. [22].

The second set of protocols are based on topology control and minimum energy routing problems. The nodes can alter their transmit power level to maintain the connectivity of the network topology, while increasing network capacity, and reducing interference and energy consumption. Here, SIR threshold, transmit power and received signal strength are generally used to find the minimum transmission power required between any two nodes in the network. Such protocols usually prefer several short hops to one long hop, as these have been found to reduce interference and contention in the network. [10] presents a protocol for finding the common lowest transmit power for all the nodes in the network, while maintaining network connectivity. Several routing daemons are proposed to run in parallel, one for each power level so that correct transmit power can be chosen at routing layer. [20, 16] present some topology control algorithms based on the geometric properties of the network. The protocol in [12] tries to limit the degree of the nodes by forming Minimum Spanning Tree (MST) based on local connectivity. PARO [5] uses a cost function based on transmit power level, and if intermediate nodes can forward with less total power, they offer to become the re-directors of packets. Similarly, [9] used hello messages to distribute transmission power, and uses the minimum power required to connect to a neighbor, while considering the costs of reception of a packet at the neighboring nodes.

Next set consists of routing for maximum network lifetime. In papers like [15, 1, 17, 18], routing is done by using an appropriate metric for optimization of power consumption of the network interface per packet, while taking into account the battery reserves at the nodes.

Few other protocols make use of the power save mode available in the network interface to reduce energy consumption. Since there is no central entity to control the sleep and wake up periods, some distributed control mechanism is required for such protocols. Example of such protocols are PAMAS [13], where the nodes sleep while overhearing packets not addressed to it, and protocols like SPAN [2], and GAF [23] where some of the nodes decide to stay up and handle the routing according to the topological properties of the network.

2.3 Measurement of energy consumption

Since energy is a scarce and non-renewable resource in wireless ad hoc networks, energy-efficient protocol design is a key concern. The design and performance analysis of such protocols require proper modeling for the measurement of energy consumption. Feeney *et al.* [4, 3] presented some results of measuring energy consumptions of various network interfaces. Four possible energy consumption states are identified: transmit, receive, idle and sleep. The first two state are when the node is transmitting and receiving packets respectively, the idle state is when the node is waiting for any packet transfers, and the sleep state is a very low power state where the node can neither receive nor transmit.

The cost associated with each packet at a node is represented as the total of incremental cost m proportional to the packet $size$ and a fixed cost b associated with channel acquisition:

$$Cost = m \times size + b \tag{2}$$

Thus, the cost of a broadcast packet will be of the form

$$\begin{aligned} Cost_{broadcast} &= m_{send} \times size + b_{send} \\ &\quad + \sum_{n \in S} (m_{recv} \times size + b_{recv}) \end{aligned} \tag{3}$$

where

$$\begin{aligned} S &= \text{set of nodes within transmission range} \\ &\quad\ \text{of transmitting node} \\ m_{send}, b_{send} &= \text{incremental and fixed cost for} \\ &\quad\ \text{sending the broadcast packet,} \\ m_{recv}, b_{recv} &= \text{incremental and fixed cost for} \\ &\quad\ \text{receiving the broadcast packet.} \end{aligned}$$

Similarly, the cost of point-to-point traffic at the sender and receiver while considering presence of RTS/CTS control messages in 802.11 based networks can be respectively represented by the following equation:

$$\begin{aligned} Cost_{unicast\_sender} &= b_{sendctl} + b_{recvctl} \\ &\quad + m_{send} \times size + b_{send} + b_{recvctl} \end{aligned} \tag{4}$$

$$\begin{aligned} Cost_{unicast\_receiver} &= b_{recvctl} + b_{sendctl} \\ &\quad + m_{recv} \times size + b_{recv} + b_{sendctl} \end{aligned} \tag{5}$$

where

$$\begin{aligned} b_{sendctl} &= \text{fixed cost for sending a control packet,} \\ b_{recvctl} &= \text{fixed cost for receiving a control packet.} \end{aligned}$$

Besides this model for energy costs, it was also shown that the energy consumed by an idle network interface dominates the total energy consumption (about a magnitude more than sleep mode).

Developing on this energy model, we present a simple model to calculate the energy spent at each node due to the flows present in the network. Using the power consumption values for transmit and receive state as measured in Feeney's results, we show through simulations in NS-2 that in an ideal network without any interference and collisions, our model gives exact measurement of energy consumption in nodes due to a flow in the network. Then this model is used to compare the energy consumption in non-ideal simulation settings to evaluate the effect of interference and collision on energy. In fact, similar model can be used to measure other parameters of the network like bandwidth [11] in order to carry out performance evaluation of routing protocols.

3 Model and measurement

The energy spent at each node due to a flow can be calculated in a simple way according to our model. Figure 1 shows the model that was used. Depending on whether the node belongs to a flow or not and where in the flow the node in question or nodes effecting it are situated, the total energy expenditure at a node due to another node in the network can be calculated as follows:

$$\begin{aligned} E_{N/M} &= \mathbb{1}_{n>0}(\mathbb{1}_{M=N}E_{T_{ack}} + \mathbb{1}_{M\neq N}E_{R_{ack}}) \\ &\quad +\mathbb{1}_{m>0}(\mathbb{1}_{M=N}E_{T_{pck}} + \mathbb{1}_{M\neq N}E_{R_{pck}}) \end{aligned} \tag{6}$$

where

$$\begin{aligned} E_{N/M} &= \text{energy spent at node N due to node M,} \\ E_{T_{ack}} &= \text{energy spent for transmission of one} \\ &\quad \text{acknowledgement packet,} \\ E_{T_{pck}} &= \text{energy spent for transmission of one} \\ &\quad \text{data packet,} \\ E_{R_{ack}} &= \text{energy spent for reception of one} \\ &\quad \text{acknowledgement packet,} \\ E_{R_{pck}} &= \text{energy spent for reception of one} \\ &\quad \text{data packet} \\ \mathbb{1}_p &= \begin{cases} 1 & p \text{ is true,} \\ 0 & \text{otherwise.} \end{cases} \end{aligned}$$

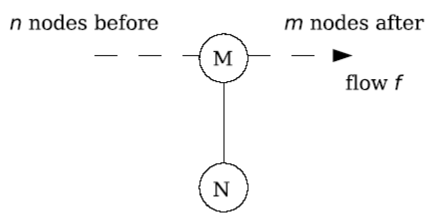


Figure 1: Effect on node N due to node M in flow f

4 Simulation

Using the model presented in the previous section, a number of simulations were done in NS-2 to experiment with energy consumption in wireless ad hoc networks, where the flows affect/interfere with each other. The main aim was to measure energy at the nodes in the flow and see how the energy consumption is affected by interference from other flows, so that effect of collisions can be observed. The simulation settings and results will be discussed next.

4.1 Simulation settings

Nodes have the default transmission range of 250m and a Carrier Sense range of 500m. The RTS/CTS option is turned off in the MAC layer. Various Constant Bit-Rate (CBR) flows at a bit rate of 250kbps are considered for the simulation time of 600s each. The size of the data packets is set at 1.5 KB.

4.2 Calculation of energy required for transmission and reception of a single packet

4.2.1 For data packets

Packet length = 1500 bytes,
Bit rate = 250 kbps (48 ms/packet or 20.8 packets/sec)
Total packet size = size of (preamble + PLCP header + MAC header + IP header + data) $= (144 + 48 + 28 \times 8 + 20 \times 8 + 1500 \times 8)$ bits (default values, as used in NS-2).
Although, the preamble and PLCP header are transmitted at 1Mbps while the rest are sent at 11 Mbps. Thus, we have 144 + 48 bits sent at 1 Mbps, with a transmission time for single packet = 0.19 ms.
With 8×1548 bits sent at 11 Mbps, the transmission time for a single packet is $\frac{8\times1548}{11\times10^6} =$ 1.128 ms.
Hence the total transmission time for a single packet = 1.128 + 0.19 = 1.318 ms

4.2.2 For ACK packets

Packet length = 14 bytes, bit rate = 250 kbps
Total packet size = size of (preamble + PLCP header + ACK) $= (144 + 48 + 14 \times 8)$ bits
So, transmission time for single packet = 0.304 ms

4.2.3 Calculation of energy spent

For the simulation, the typical transmission and reception cost for Lucent Silver card as specified in [3, 4] was used. Thus, transmission power used was 1.3 mW, and reception power was 0.9 mW. Thus, the various energy cost components were

$$
\begin{aligned}
E_{T_{pck}} &= 1.3 \times 1.318 \times 10^{-3} = 1.713mW \\
E_{R_{pck}} &= 0.9 \times 1.318 \times 10^{-3} = 1.186mW \\
E_{T_{ack}} &= 1.3 \times 304 \times 10^{-6} = 0.395mW \\
E_{R_{ack}} &= 0.9 \times 304 \times 10^{-6} = 0.274mW
\end{aligned}
$$

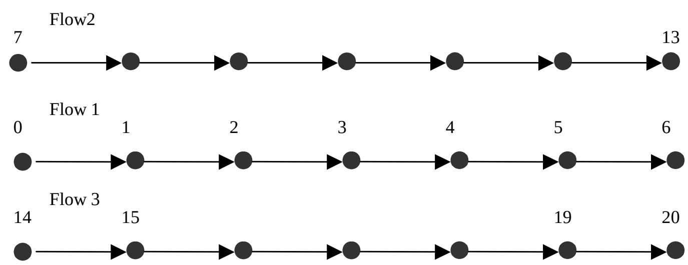
Thus, using the energy calculation equation (6), the energy for the flow as shown below was calculated for each node in the flow shown below:

$$0 \longrightarrow 1 \longrightarrow 2 \longrightarrow 3 \longrightarrow 4 \longrightarrow 5 \longrightarrow 6$$

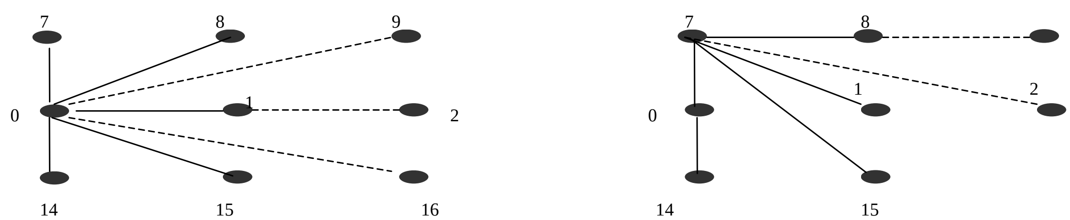
For node 0:

$$\begin{aligned}
E_{0/0} &= E_{T_{pck}} = 1.713mW \\
E_{0/1} &= E_{R_{ack}} + E_{R_{pck}} = 1.46mW \\
E_{0/2} &= E_{R_{ack}} + E_{R_{pck}} = 1.46mW \\
\mathbf{E_0} &= 4.633mW
\end{aligned}$$

Similarly, energy was calculated for other nodes. The calculated values were compared with the energy expenditure of the nodes per second (first, the results above have to be multiplied by 20.8 for the number of packets being generated by the flow per second). The difference in the two energy levels gave the excess energy lost due to packet collisions during the simulation. Other more complex scenarios were then tested. The first one consists of



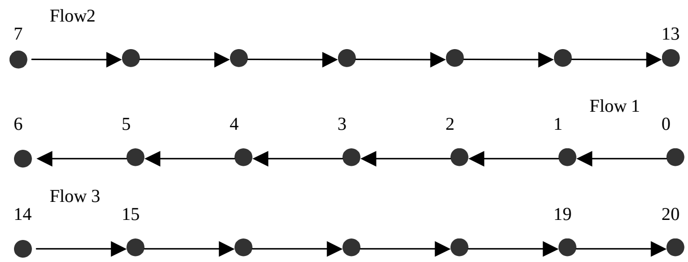
(a) Flows



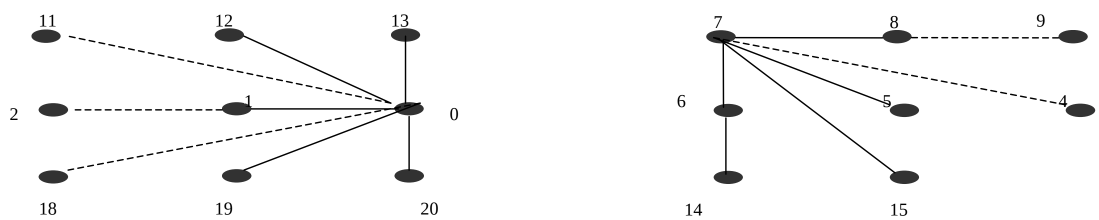
(b) Neighbors and interfering nodes shown with lines and dashed lines respectively for node 0 and 7

Figure 2: Simulation network with 3 flows.

three flows, each flow consisting of 7 nodes (see Figure 2), and the second one consists of 4 flows in a network with 200 nodes created randomly in random locations (see Figure 6)



(a) Flows



(b) Neighbors and interfering nodes shown with lines and dashed lines respectively for node 0 and 7

Figure 3: Simulation network with 3 flows, middle in opposite direction. Neighbors and interfering nodes are as shown in figure 2.

5 Discussion and analysis of results

5.1 Single flow

In the simple case of a single flow, the objective was to find the correctness of the formula calculated above (6). Since there was no interference involved, it was expected that the simulated and calculated values should match. It was found that the calculated and simulated energy levels were exactly the same, proving the correctness of the formula.

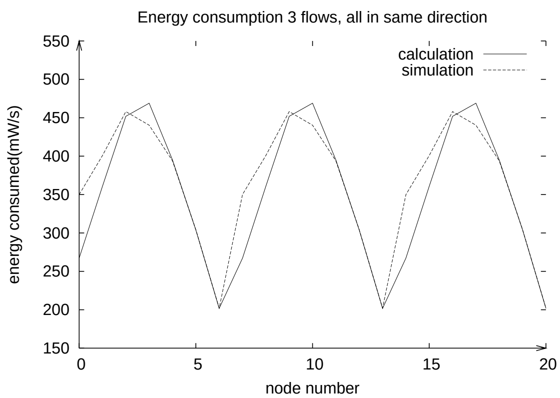
5.2 Three flows

For the case with 21 nodes and 3 flows, two cases were considered, one where all the flows are in the same direction (Figure 2) and one where flow 1 is in the opposite direction (Figure 3). The result of the simulation is as shown in Figure 4.

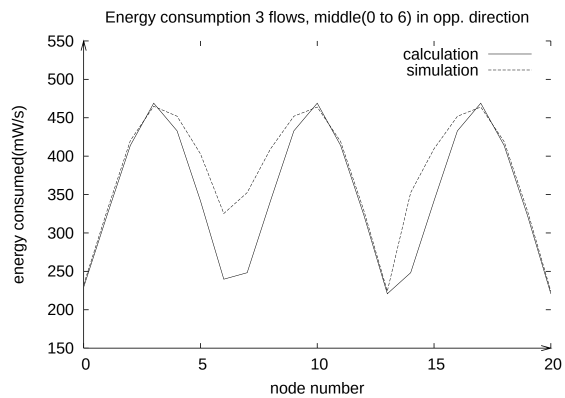
From the results, there is a larger difference in the calculated and simulated energy consumption in the source nodes (up to about 83mW/sec), showing that these nodes have to transmit and receive more, most probably due to collisions. This can be explained, for example, for flow 1, nodes 0 and 3 can transmit at the same time, since they are not in the carrier sense region of each other, but 3 acts as a hidden node to node 0, causing collisions at node 1. This is verified by figure 5, which shows the number of packets destined/forwarded to the nodes that were lost due to collisions and also the number of retransmissions by the nodes. It is seen that for the first flow, lots of packets forwarded to node 1 from node 0 are lost due to collisions, requiring node 0 to retransmit them. Since transmission requires more energy than reception, node 0 shows more energy consumption due to retransmission than node 1 due to reception of the retransmitted packets. Similar behaviour is seen in nodes of other flows, cause more energy loss at nodes that retransmit and some energy loss in the colliding nodes due to reception of the retransmitted packets. Please see section 6 for more discussion of these results on collision.

The results show that source nodes experience about 31% increase in energy consumption due to collisions. It is also noticed that some node actually consume less energy than that calculated. This is due to the fact that, when doing the calculation, we assume that each flow is continuous, creating/forwarding a new packet for each packet interval at each node, causing energy consumption at nodes in the flow and nearby. However, due to various factors like backoff due to the medium being busy, packets being lost and needing retransmissions due to collisions, and delay before and ACK is received due to the previous reasons, the flow is not actually continuous. The final energy measured, which is the average energy spent by nodes each second, can be lower if a node is not able to transmit some packets during the simulation time due to long delays.

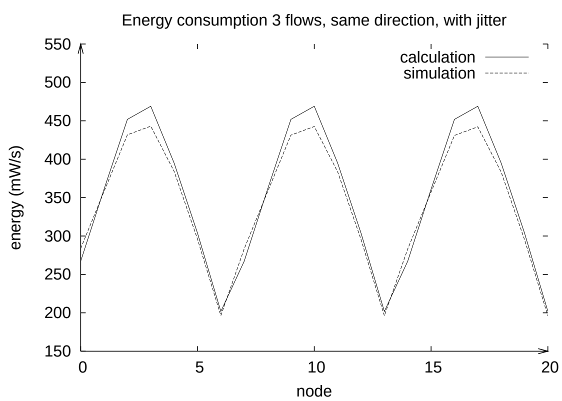
When the flow in the middle is in the opposite direction (note that, although the flow is still from node 0 to node 6, the position of these nodes are interchanged), the difference in energy is greater, up to 42%. In the middle flow, the effect of collisions and retransmissions is maximum for the end nodes (node 4, 5, 6), while it is more for the source node and other nodes in beginning of the flow in the other two flows. It shows that the source nodes in



(a) All flows in the same direction

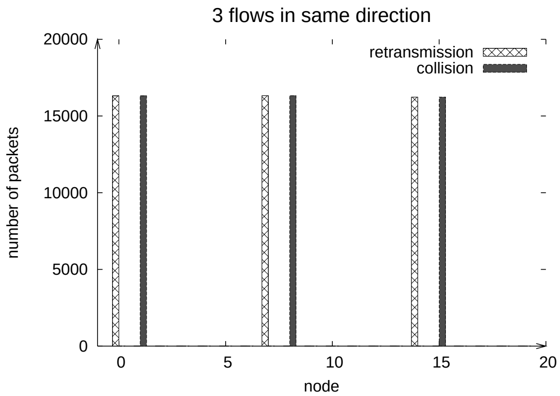


(b) Middle flow in the opposite direction

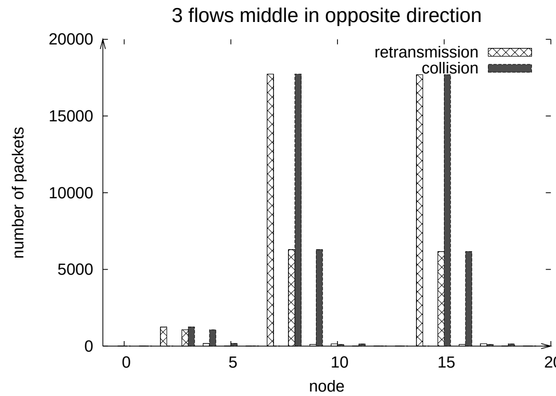


(c) All flows in the same direction with jitter added

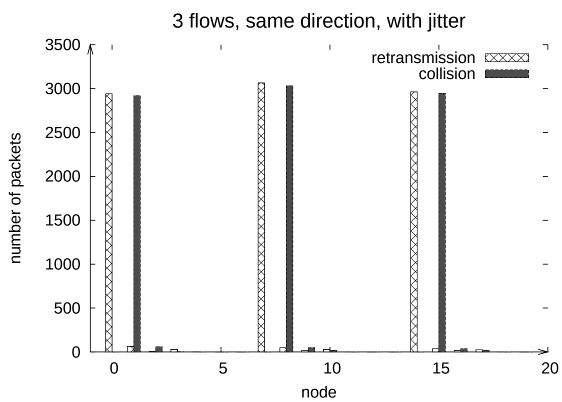
Figure 4: Energy consumption rate of nodes in the network with 3 flows



(a) All flows in the same direction



(b) Middle flow in the opposite direction



(c) All flows in the same direction with jitter added

Figure 5: Number of packets that caused extra energy consumption (due to collisions and retransmissions) of nodes in the network with 3 flows

flows 2 and 3 effect the node 4, 5, 6 the greatest. As mentioned above, node 3 still causes collisions in node 1 in flow 1, but due to collisions in the flows 3 and 4, the source nodes transmit/retransmit more packets causing more energy loss at these three nodes. This shows that inter-flow collisions can cause a significant amount of energy consumption.

When evaluating flows at the same rate and when all the flows are started at the same time, collisions are more likely to take place than when there is some delay between the flows. When a jitter is added, collisions decrease by a large amount. In the simulation (see Figure 4(c)), some jitter is added between the flows so that the second flow starts just after the first flow finishes the transmission of 1 packet (assuming no collision), so that inter-flow collisions are greatly reduced. In this case, the increase in energy is now reduced to about 19%, but overall, the energy consumption is more balanced, and introduces less collisions than in no jitter cases. The number of retransmissions are thus greatly reduced, as can be seen in figure 5.

5.3 Four flows in a random network

For the case of 200 nodes and 4 flows, 4 cases were considered:

- SIR is cumulative, no jitter between the flows,
- SIR is cumulative, jitter present between the flows,
- SIR is non-cumulative, no jitter between the flows,
- SIR is non-cumulative, jitter present between the flows.

By default, NS-2 uses a non-cumulative SIR model, where the noise from the longest signal is taken to calculate the SIR for each reception. This model does not accurately represents the real environment.

In our model, a cumulative SIR model is added, where the noise taken was the sum of reception power of all signals that could be heard at the node receiving a packet, and reception is successful only if the new SIR is greater than the carrier sense threshold.

The results of the simulations for the energy consumption rate of some nodes, among 200 randomly placed nodes, are shown in Figures 7 (without jitter and with non- cumulative SIR Model) and 8 (with jitter and cumulative SIR Model). For each node presented, the calculated (left) and simulated (right) energy values are presented.

For this network and flow settings, the results were similar to that of the three flows cases: the source nodes shows the most energy loss. In the default case, with no jitter and SIR non-cumulative, collisions may increase the energy consumption by up to 45.4%. The introduction of jitter into the model reduces the number of collisions decreasing the energy consumption by up to 26.5%, but is about 6% in average.

Both the cases with jitter and no jitter were also compared to the case where a cumulative SIR is used, but the energy consumption while using cumulative and non-cumulative SIR model did not show significant differences.

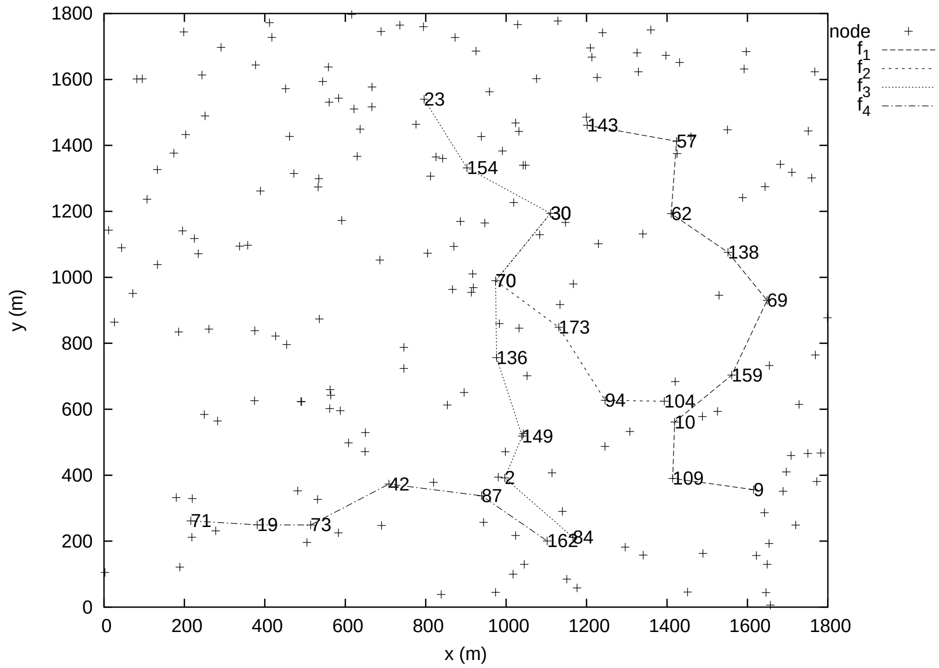
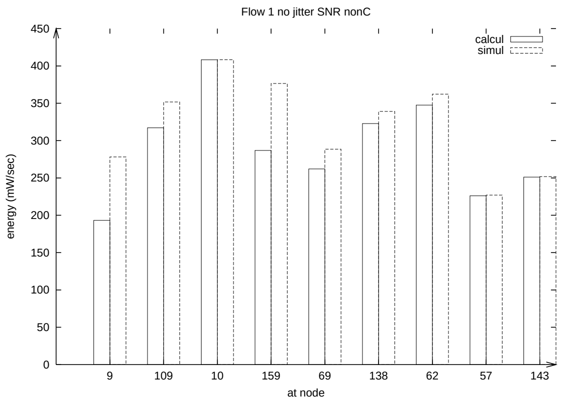
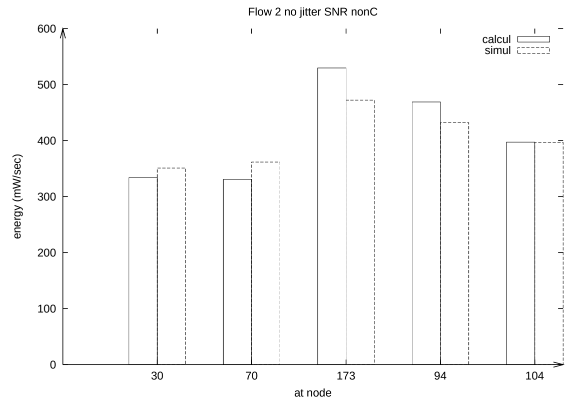


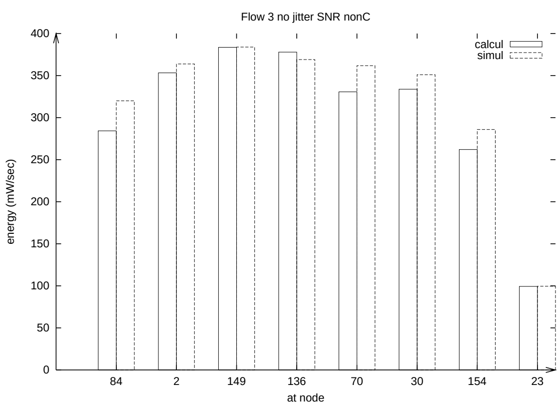
Figure 6: Simulation network with 200 randomly placed nodes and 4 flows



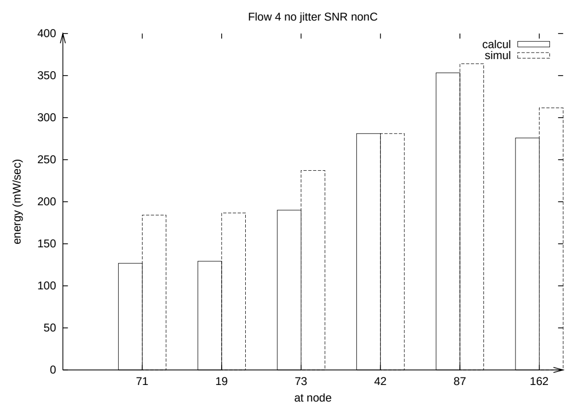
(a) Flow 1



(b) Flow 2

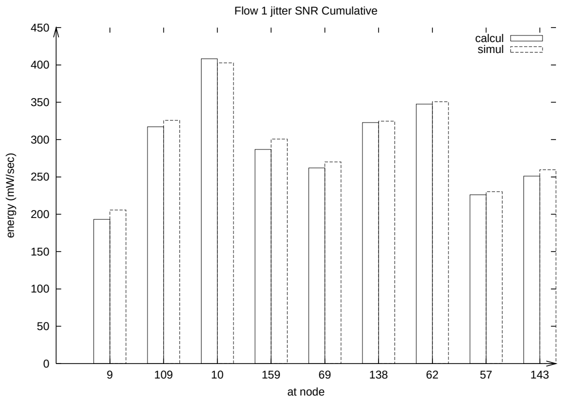


(c) Flow 3

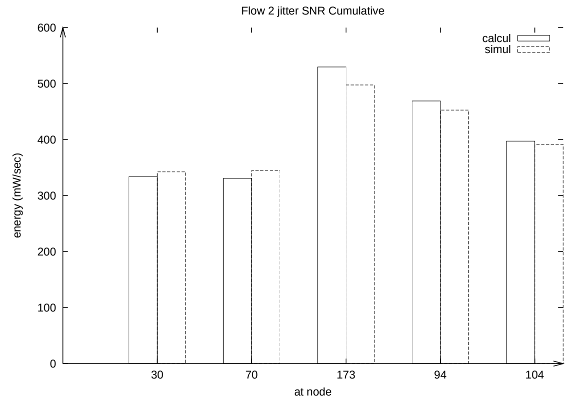


(d) Flow 4

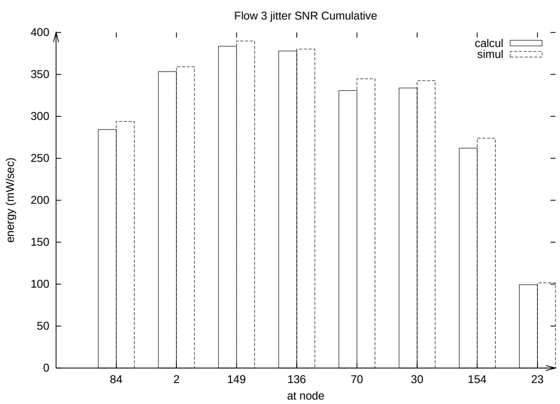
Figure 7: Energy consumption rate of the nodes of the 4 flows, without jitter and with non-cumulative SIR Model



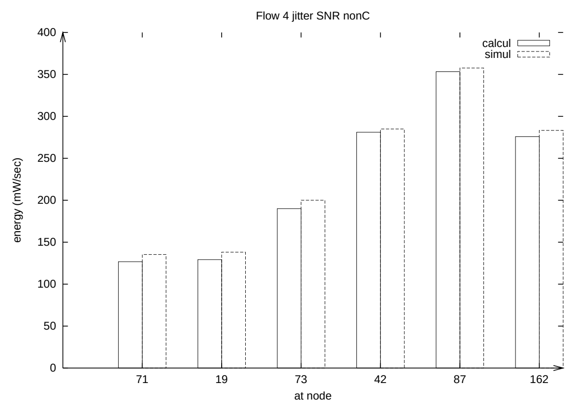
(a) Flow 1



(b) Flow 2



(c) Flow 3



(d) Flow 4

Figure 8: Energy consumption rate of the nodes of the 4 flows, with jitter and with cumulative SIR Model

Thus, it was seen that though collisions between different flows can increase the energy consumption significantly, introduction of jitter can decrease such collision probabilities. It would be interesting to extend the experiments to include more flows in very dense networks, where the carrier sense diminishes at the center of the network due to extensive interference and collisions [6, 7].

6 Collision awareness

It can be deduced from the results presented here, that collisions can effect the energy consumption of nodes in the network. The energy measurement model presented in this paper takes into account all the nodes that are in the reception area of the flow. So, not all collisions may result in more energy consumption. The main effect of collision will be at the nodes in the flow, where the packets that was forwarded to them collide, so that they have to be resent. So only these collisions were measured. As predicted, the nodes at which such collisions occur and the nodes which have to retransmit as the result, show more decrease in energy. Since transmission requires more energy than reception, nodes retransmitting show more energy consumption due to retransmission than the colliding nodes which consume more energy due to reception of the retransmitted packets.

Due to the carrier sensing mechanism and backoff procedure used when a node wants to send a packet but the channel is not idle, the probability that two transmitter nodes collide can be neglected when these nodes are neighbors. However, this is no longer the case when they do not hear each other. That is why, in this paper, we are interested in the case of collisions on a link due to hidden nodes to that link, as we assume that no RTS/CTS is used. Let us consider a link (T, R) where T is the transmitter and R is the receiver. A packet being transmitted from node T to node R encounters a collision if and only if during its transmission, a hidden node also transmits. We recall that a hidden node to the link (T, R) is any node H that can be heard from node R and can not be heard from node T. In the following, we assume that the number of hidden nodes to any link, denoted n_{hidden}, is available.

Thus, if the duration of transmission of a packet on the link (T, R) is t_{trans} and the amount of time the channel is sensed idle (no noise is detected) at node T is t_{idle}, where $t_{idle} > t_{trans}$, then the probability of collision on that packet is $p = \frac{t_{trans}}{t_{idle}}$, given that there is at least one hidden node.

Let t_{busy} be the amount of time the channel is busy at node T due to node T's own traffic and noises detected. The total amount of time node T spends due to retransmissions of a packet due to i successive collisions is given by $\Theta_i = i(t_{trans} + EIFS) + \sum_{j=1}^{i} CW_j$, where $EIFS$ is the Extended Interframe Space following reception of an erroneous frame and CW_j is the average size of the contention window at j^{th} stage according to the IEEE 802.11b standard where CW_j is given by $CW_j = CW_{min} * 2^j - 1$. Therefore, the percentage of time the channel is sensed idle after i successive collisions on the same packet is $t_i = 1 - \frac{t_{busy}+\Theta_i}{t_{arrival}}$, where $t_{arrival}$ is the inter-arrival time of packets on link (T, R).

We can now compute the amount of energy consumption at a node N due to collisions on the link (T, R), denoted $E^N_{(T,R)}$, using the collision model presented in [11], under the assumption that a packet collides at most once with a given hidden node:

$$E^N_{(T,R)} = \frac{\sum_{i=1}^{n_{hidden}} i(E^N_T + E^N_R)\delta_i}{1 + \sum_{i=1}^{n_{hidden}} \delta_i}$$

where

$$\delta_i = \frac{t^i_{trans}}{\prod_{j=0}^{i-1} t_j}$$

is the probability of encountering i successive collisions on a packet, given that at least one collision is encountered,

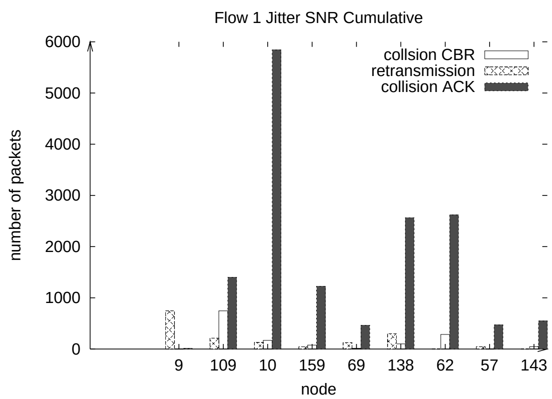
$$E^N_{N_T} = \begin{cases} E_{T_{pck}} & \text{if } N \equiv T \\ E_{R_{pck}} & \text{if } N \text{ can receive packets from } T \\ 0 & \text{otherwise,} \end{cases}$$

and

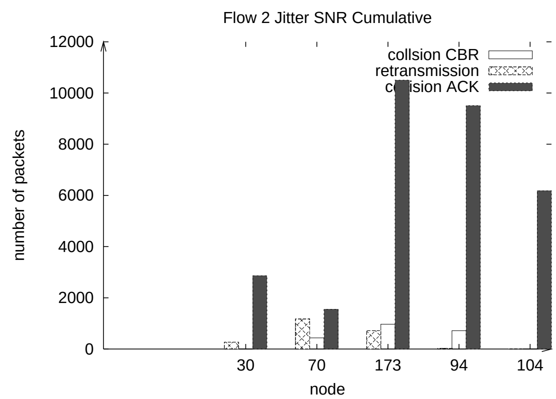
$$E^N_{N_R} = \begin{cases} E_{T_{ack}} & \text{if } N \equiv R \\ E_{R_{ack}} & \text{if } N \text{ can receive packets from } R \\ 0 & \text{otherwise.} \end{cases}$$

Let $\mathcal{L}$ be the set of links that interfere with node N; i.e. node N is in the reception area of either the transmitter or the receiver of each link. The amount of energy consumed at node N due to packet collisions of $\mathcal{L}$ is $E^N_{\mathcal{L}} = \sum_{l \in \mathcal{L}} E^N_l$.

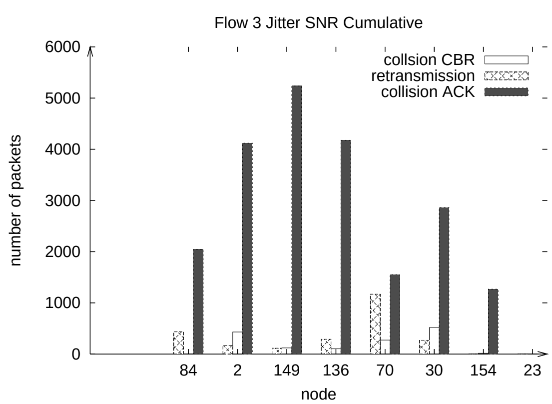
Figures 9 and 10 compare the results of packet collisions obtained by NS-2 simulations and by computation using the above formula. We use the same parameters of packet size, bit rates and node configuration for the simulations and computation as in section 4. We notice that the results obtained by computation relatively match with the ones obtained by NS-2 simulations. This shows that the collision model presented here can predict collisions in the nodes belonging to a flow and thus the energy spent because of the collisions. It should be noted again that retransmission requires more energy than reception causing retransmitting nodes to consume more energy than those receiving the packet again due to collision.



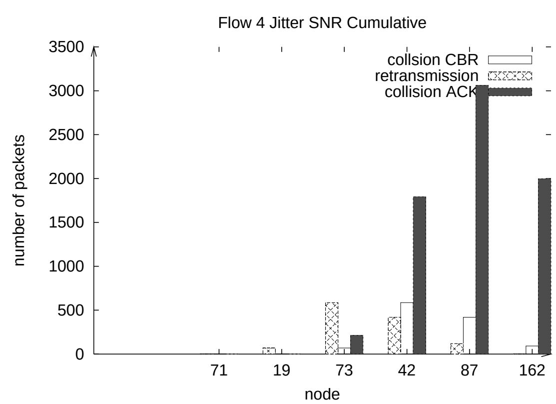
(a) Flow 1



(b) Flow 2

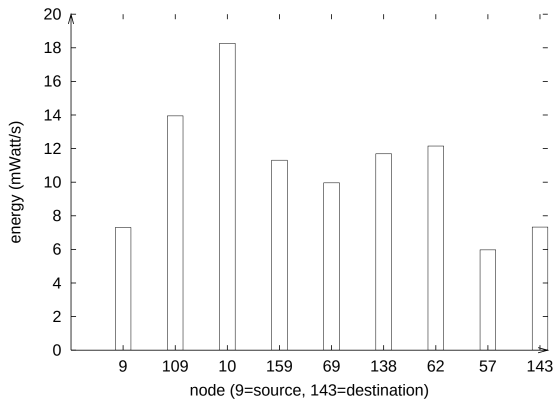


(c) Flow 3

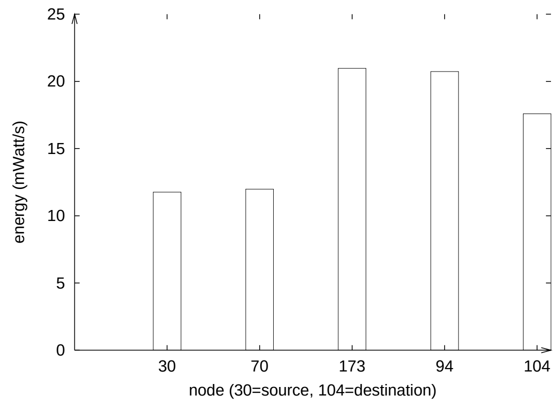


(d) Flow 4

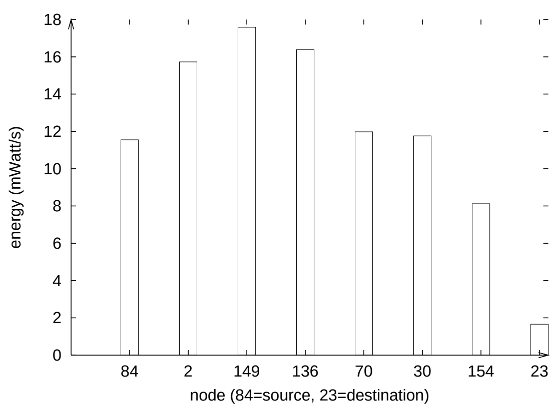
Figure 9: Number of packets that caused extra energy consumption (due to collisions and retransmissions) at the nodes of the four flows, with jitter and cumulative SIR Model, obtained by NS-2 simulations.



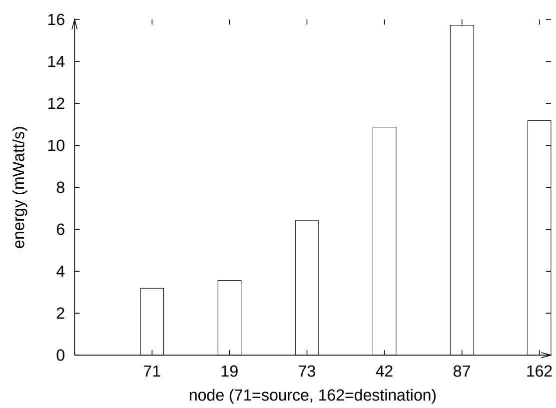
(a) Flow 1



(b) Flow 2



(c) Flow 3



(d) Flow 4

Figure 10: Amount of extra energy consumed (due to collisions and retransmissions) at the nodes of the four flows, obtained by computation.

7 Conclusion

This paper mainly presents a new model for calculating the energy consumption at a node due to various flows in the network. Such a measurement can be used for calculating costs in energy aware routing, performance evaluation of other routing protocols and even in flows requiring QoS where, besides other resource guarantees for the flow being accepted, it is also guaranteed that the selected route does not die midway.

We evaluated the accuracy of the model, and found it to give exact measurements in ideal network conditions with no interference or collisions. The model was then used to calculate the energy consumption of more complex flows, and the comparison of calculated and simulated values allowed for an evaluation of how the flows interfere with each other. Through simulations, it was shown that the flows may interfere each other, causing the energy consumption to increase up to about 46% due to the collisions that occur. It was also noticed that introducing some jitter between the flows reduce the number of collisions, decreasing the energy consumption change to about 27%. The default SIR model in NS-2 was also changed to include a cumulative model where the total interference is the sum of all the noises in the background. It was however found to bring insignificant changes in the energy consumption as compared to the default model.

Finally, since we concluded that collision is the main cause of discrepancies between our simulated result and calculated values, we tried to measure this extra energy consumed by predicting the collisions in the nodes of the network, and calculating the energy spent due to these collisions. The prediction was also found to be accurate, with the calculated values matching the values simulated. This result further strengthens the correctness of the model for energy measurement. The models presented here can be used to define the problem of minimum energy consumption and we are looking at it as a possible future extension.

Acknowledgment

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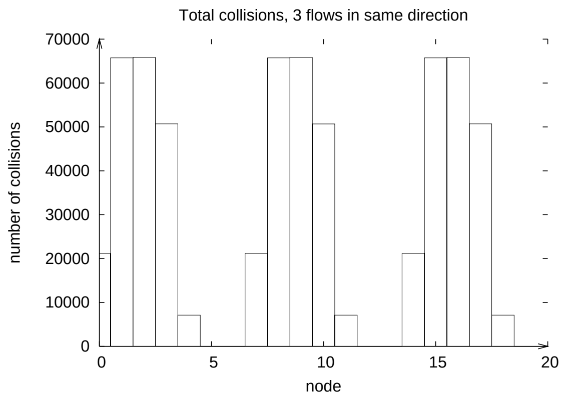
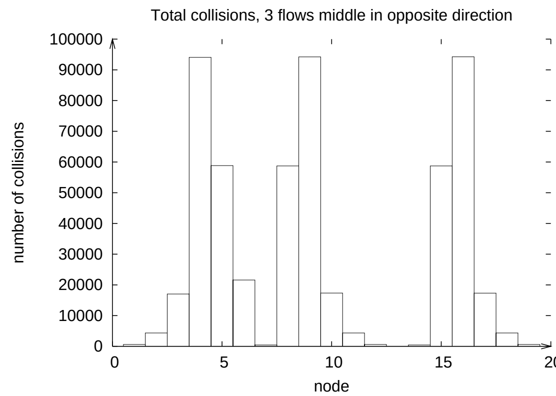
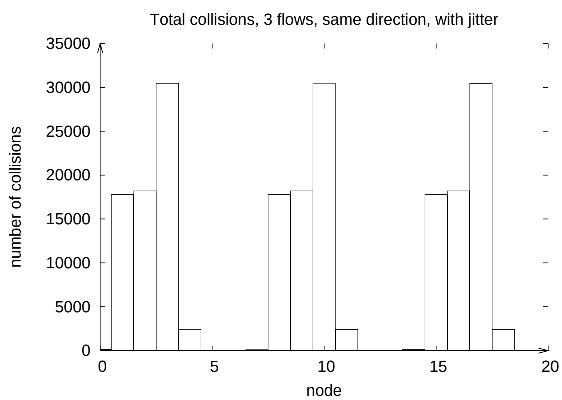
Results of the 3 flows, 21 nodes case



(a) All flows in the same direction

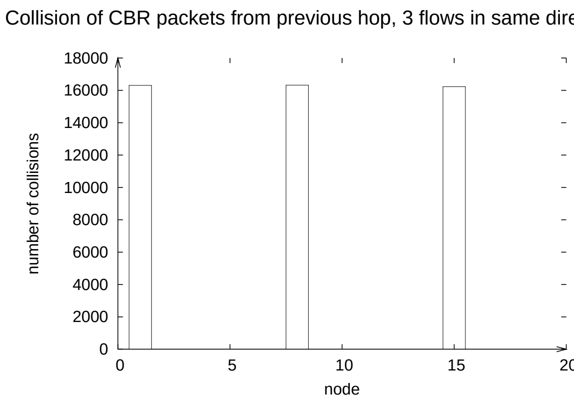


(b) Middle flow in the opposite direction

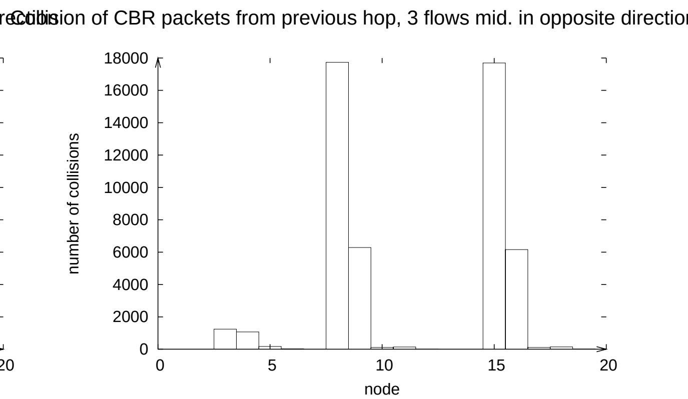


(c) All flows in the same direction with jitter added

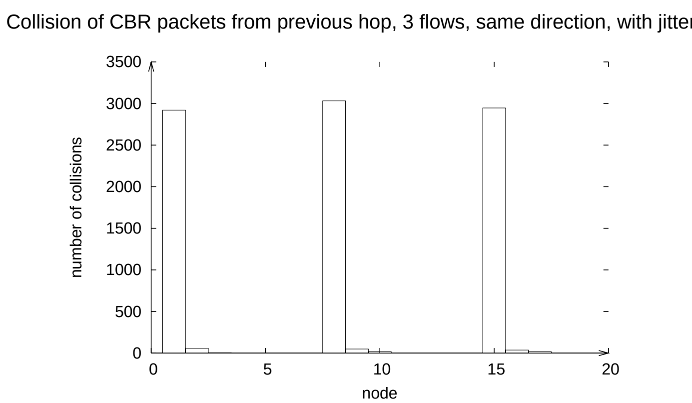
Figure 11: Total number of collisions at the nodes in the network with 3 flows



(a) All flows in the same direction

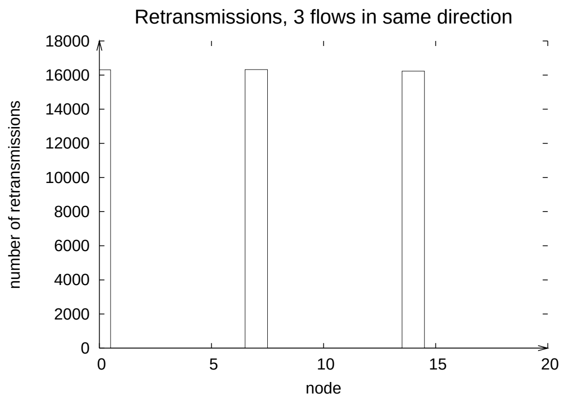


(b) Middle flow in the opposite direction

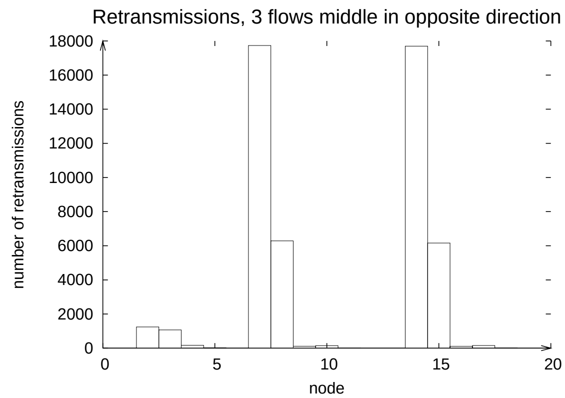


(c) All flows in the same direction with jitter added

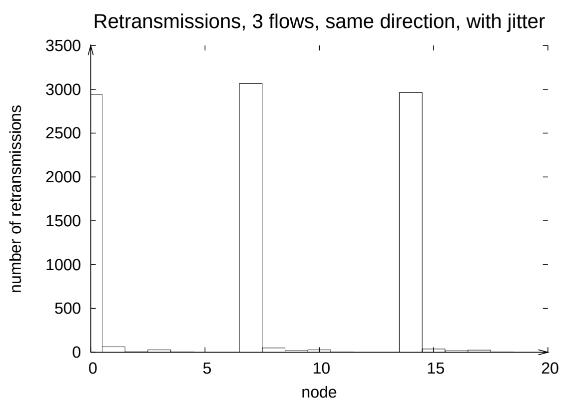
Figure 12: Total number of CBR packets from previous dropped due to collisions at the nodes in the network with 3 flows



(a) All flows in the same direction



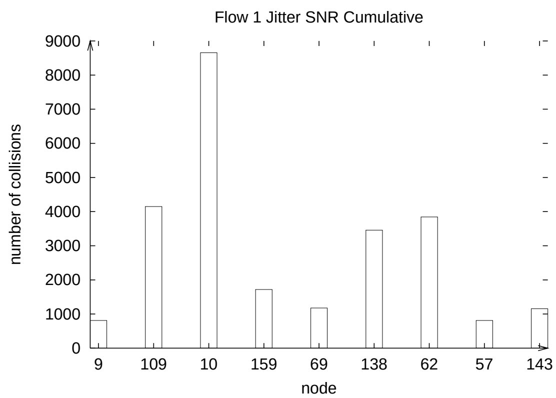
(b) Middle flow in the opposite direction



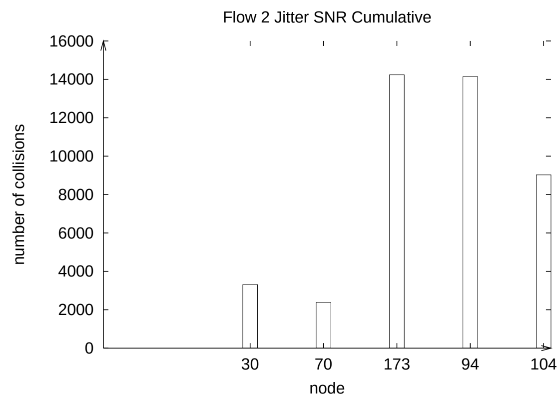
(c) All flows in the same direction with jitter added

Figure 13: Total number of retransmissions at the nodes in the network with 3 flows

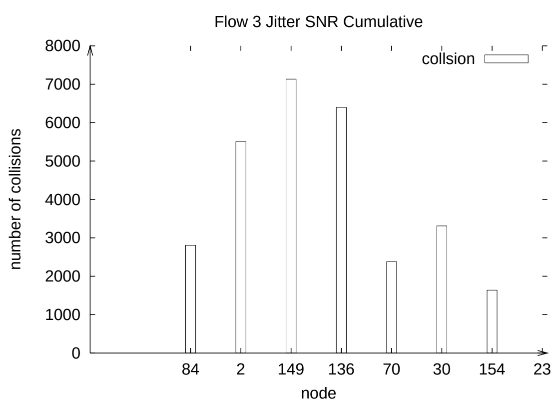
Results of the 4 flows, 200 nodes case, with jitter and cumulative SIR Model



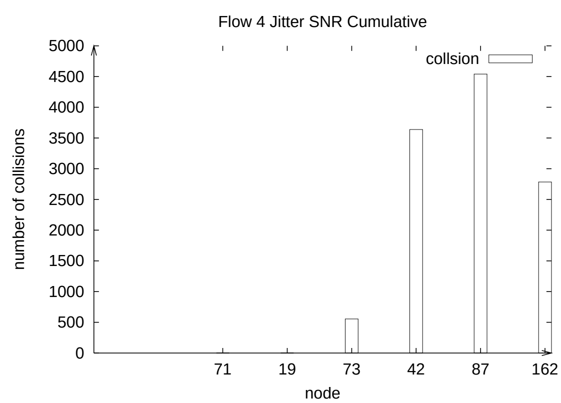
(a) Flow 1



(b) Flow 2

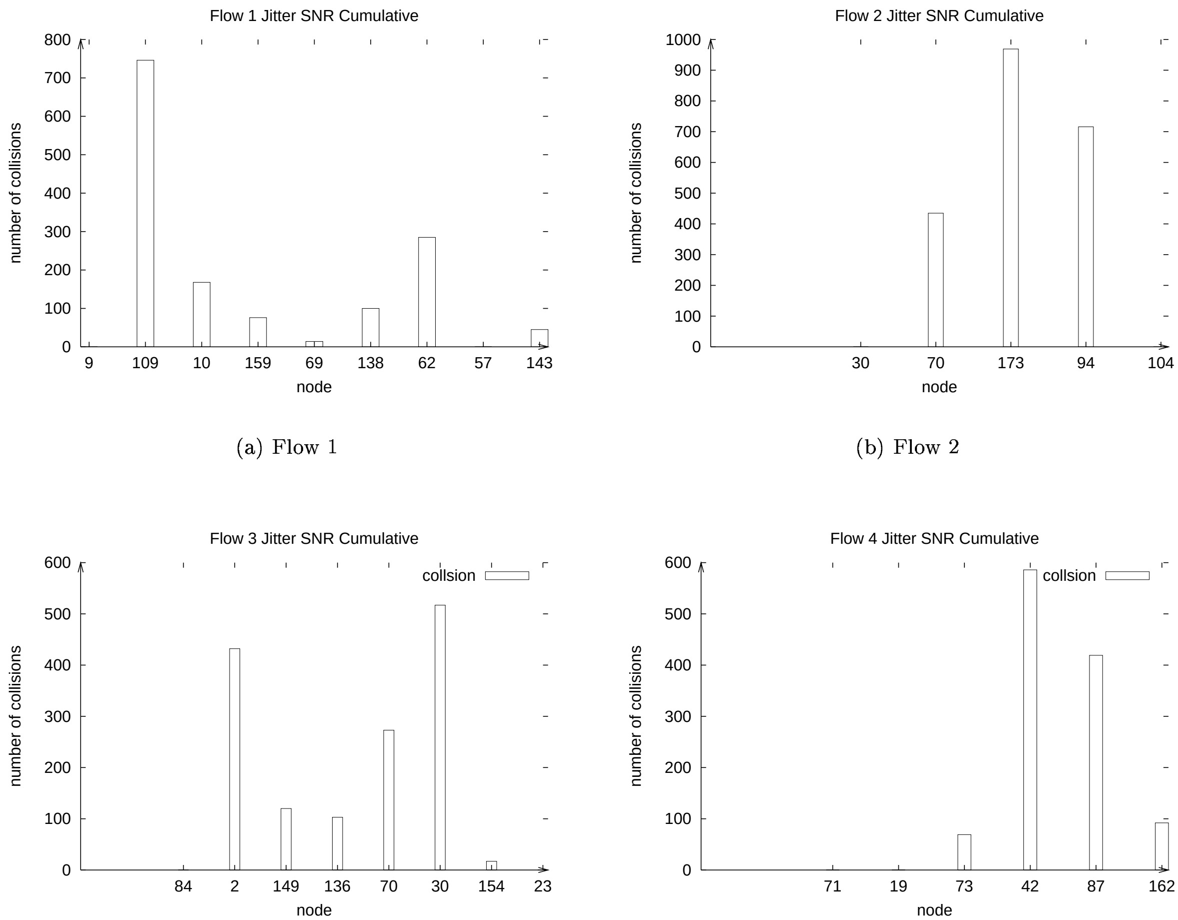


(c) Flow 3



(d) Flow 4

Figure 14: Total collisions at the nodes of the 4 flows, with jitter and cumulative SIR Model



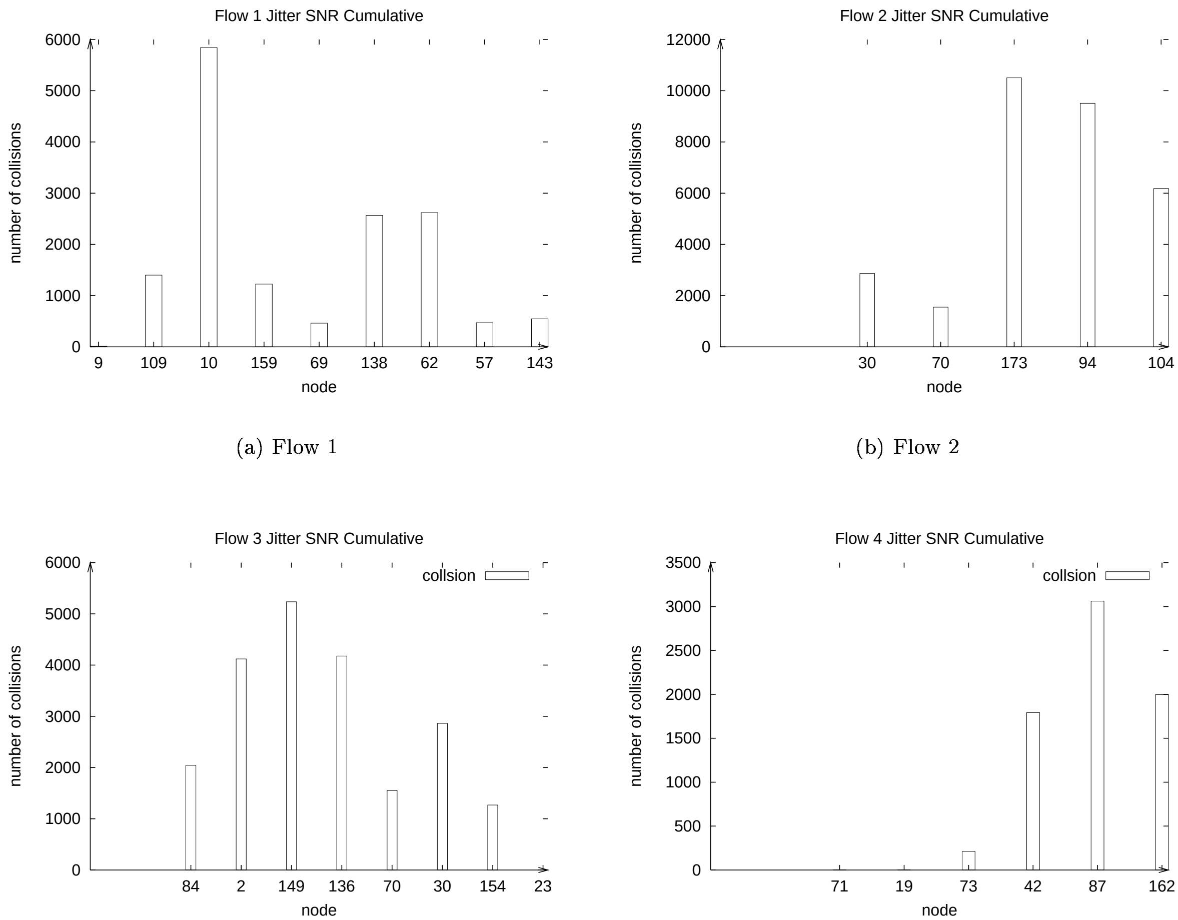
(a) Flow 1

(b) Flow 2

(c) Flow 3

(d) Flow 4

Figure 15: Total number of CBR packets from previous dropped due to collisions at the nodes of the 4 flows, with jitter and cumulative SIR Model



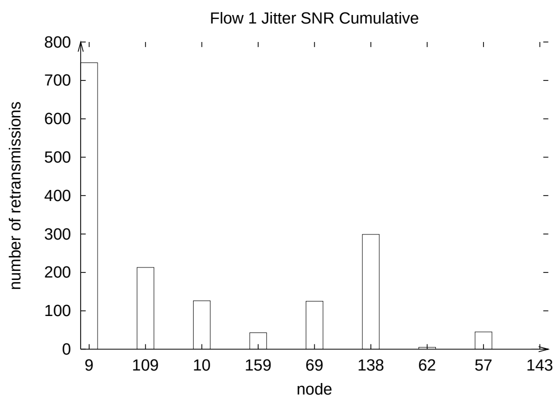
(a) Flow 1

(b) Flow 2

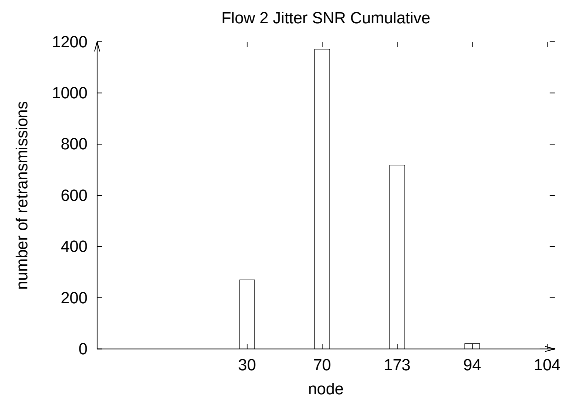
(c) Flow 3

(d) Flow 4

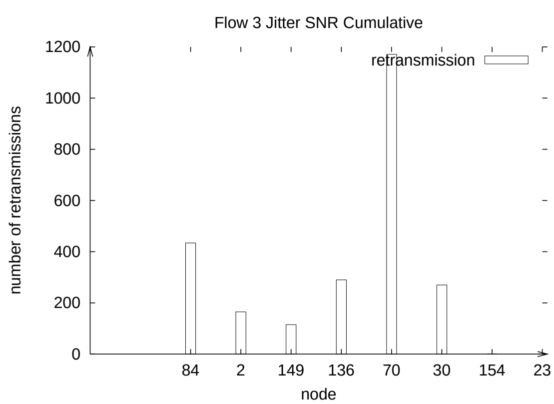
Figure 16: Total number of ACK packets destined to itself dropped due to collisions at the nodes of the 4 flows, with jitter and cumulative SIR Model



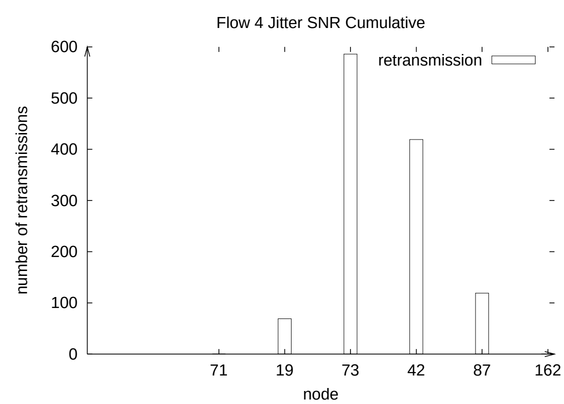
(a) Flow 1



(b) Flow 2



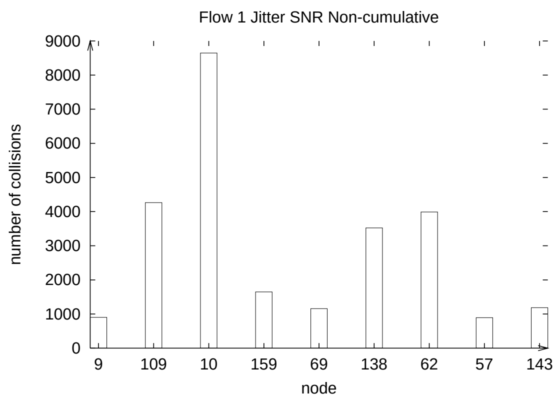
(c) Flow 3



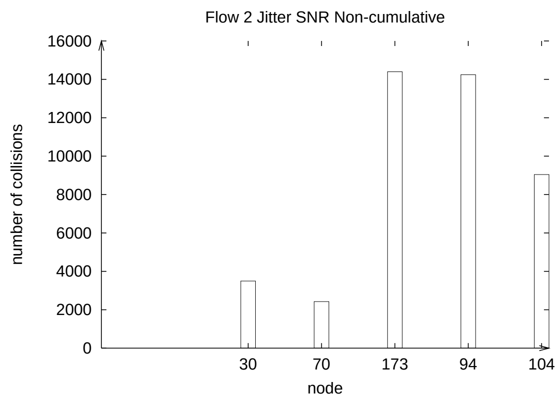
(d) Flow 4

Figure 17: Total number retransmission at the nodes of the 4 flows, with jitter and cumulative SIR Model

Results of the 4 flows, 200 nodes case, with jitter and non-cumulative SIR Model



(a) Flow 1



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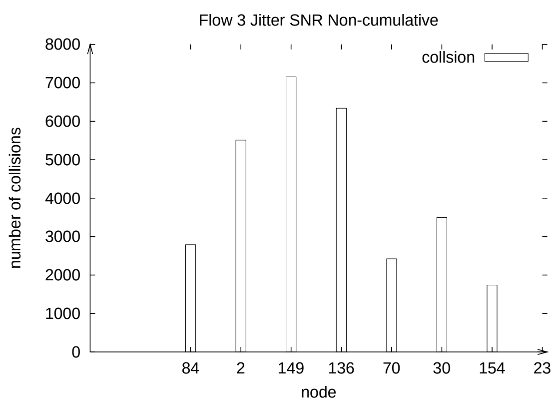
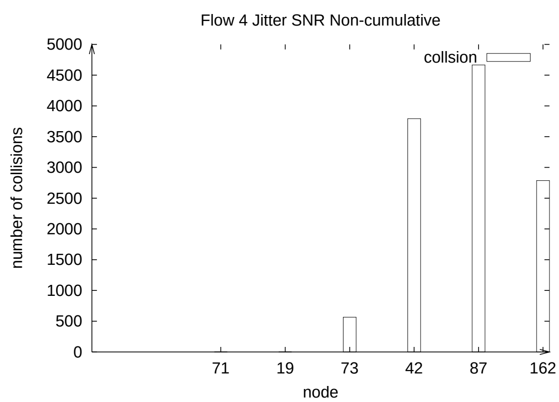
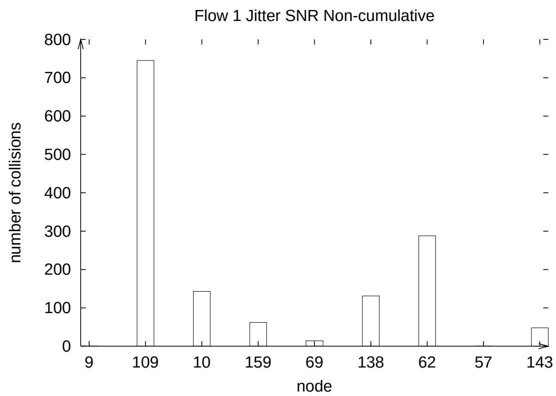


(c) Flow 3

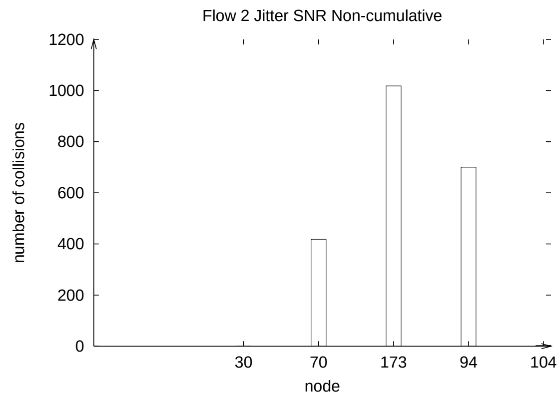


(d) Flow 4

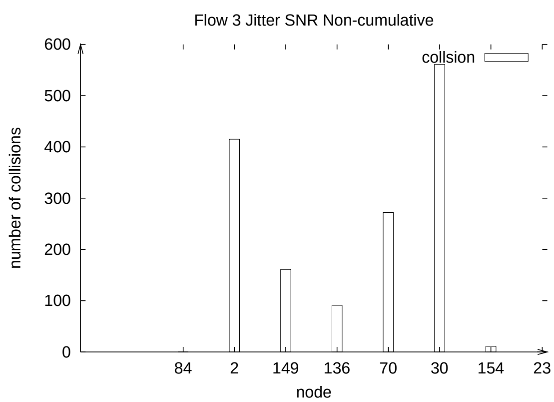
Figure 18: Total collisions at the nodes of the 4 flows, with jitter and non-cumulative SIR Model



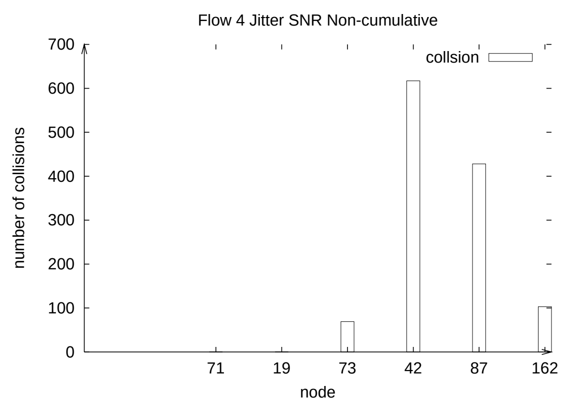
(a) Flow 1



(b) Flow 2

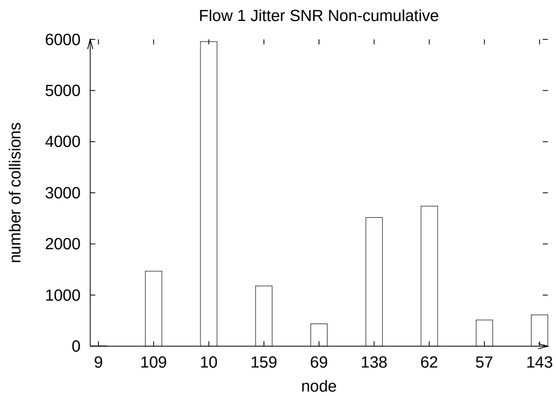


(c) Flow 3

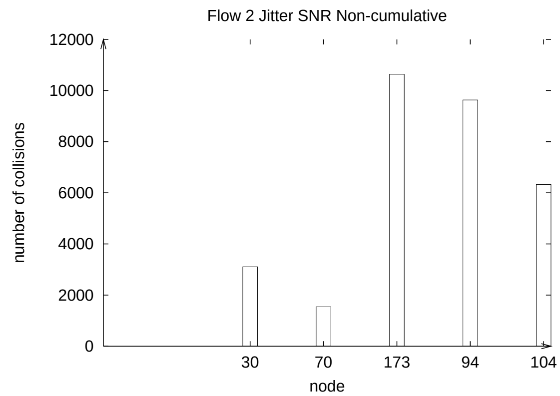


(d) Flow 4

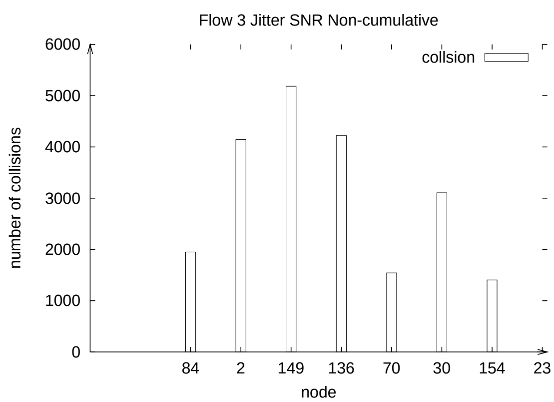
Figure 19: Total number of CBR packets from previous dropped due to collisions at the nodes of the 4 flows, with jitter and non-cumulative SIR Model



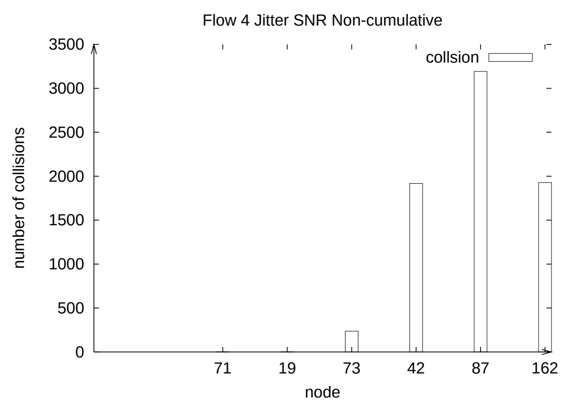
(a) Flow 1



(b) Flow 2

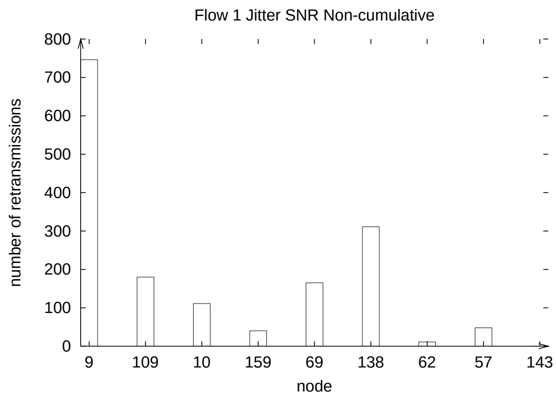


(c) Flow 3

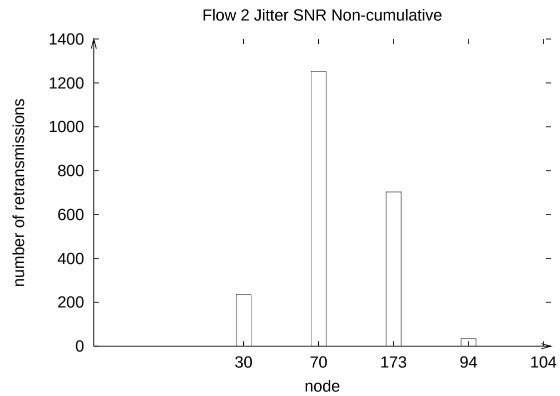


(d) Flow 4

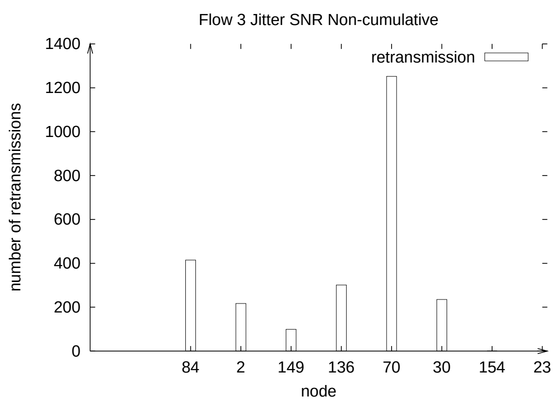
Figure 20: Total number of ACK packets destined to itself dropped due to collisions at the nodes of the 4 flows, with jitter and non-cumulative SIR Model



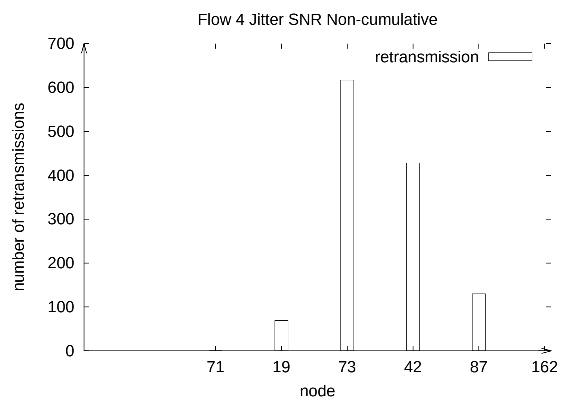
(a) Flow 1



(b) Flow 2

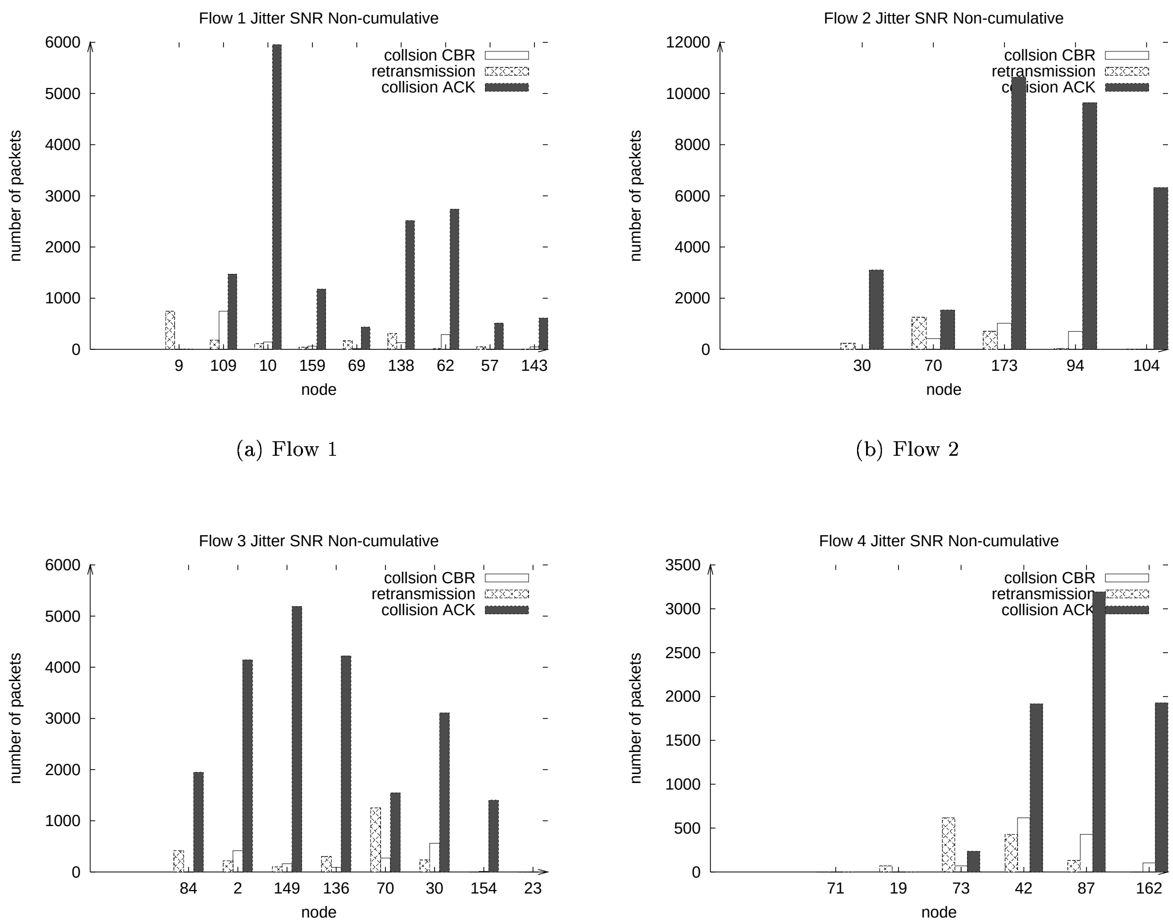


(c) Flow 3



(d) Flow 4

Figure 21: Total number retransmission at the nodes of the 4 flows, with jitter and non-cumulative SIR Model

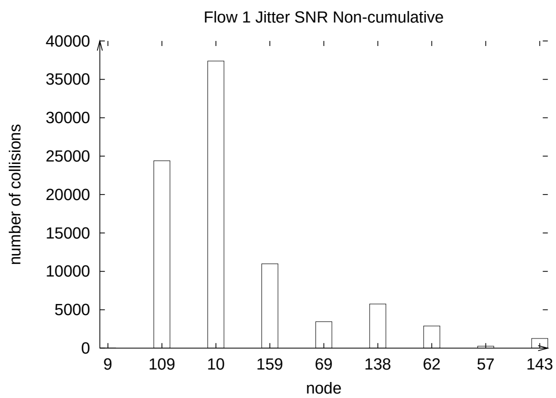


(a) Flow 1 (b) Flow 2

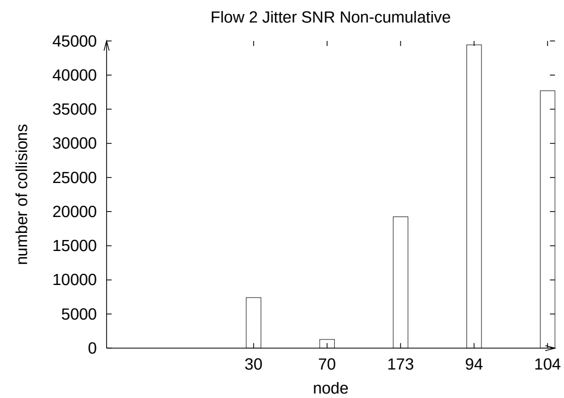
(c) Flow 3 (d) Flow 4

Figure 22: Number of packets that caused extra energy consumption (due to collisions and retransmissions) at the nodes of the 4 flows, with jitter and non-cumulative SIR Model

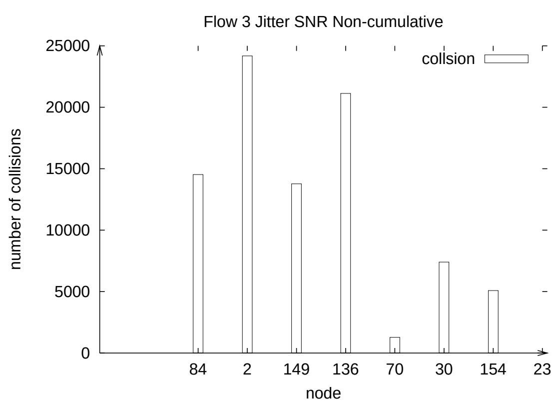
Results of the 4 flows, 200 nodes case, with no jitter and cumulative SIR Model



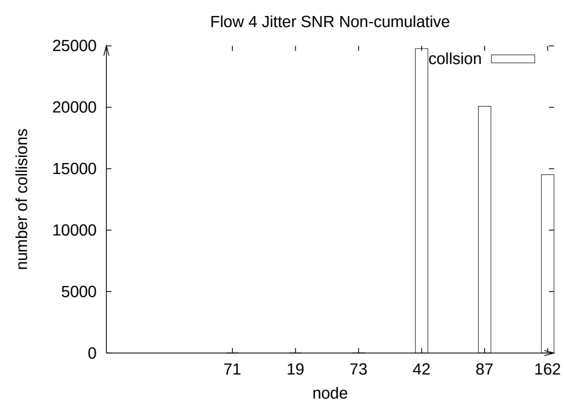
(a) Flow 1



(b) Flow 2



(c) Flow 3



(d) Flow 4

Figure 23: Total collisions at the nodes of the 4 flows, with no jitter and cumulative SIR Model

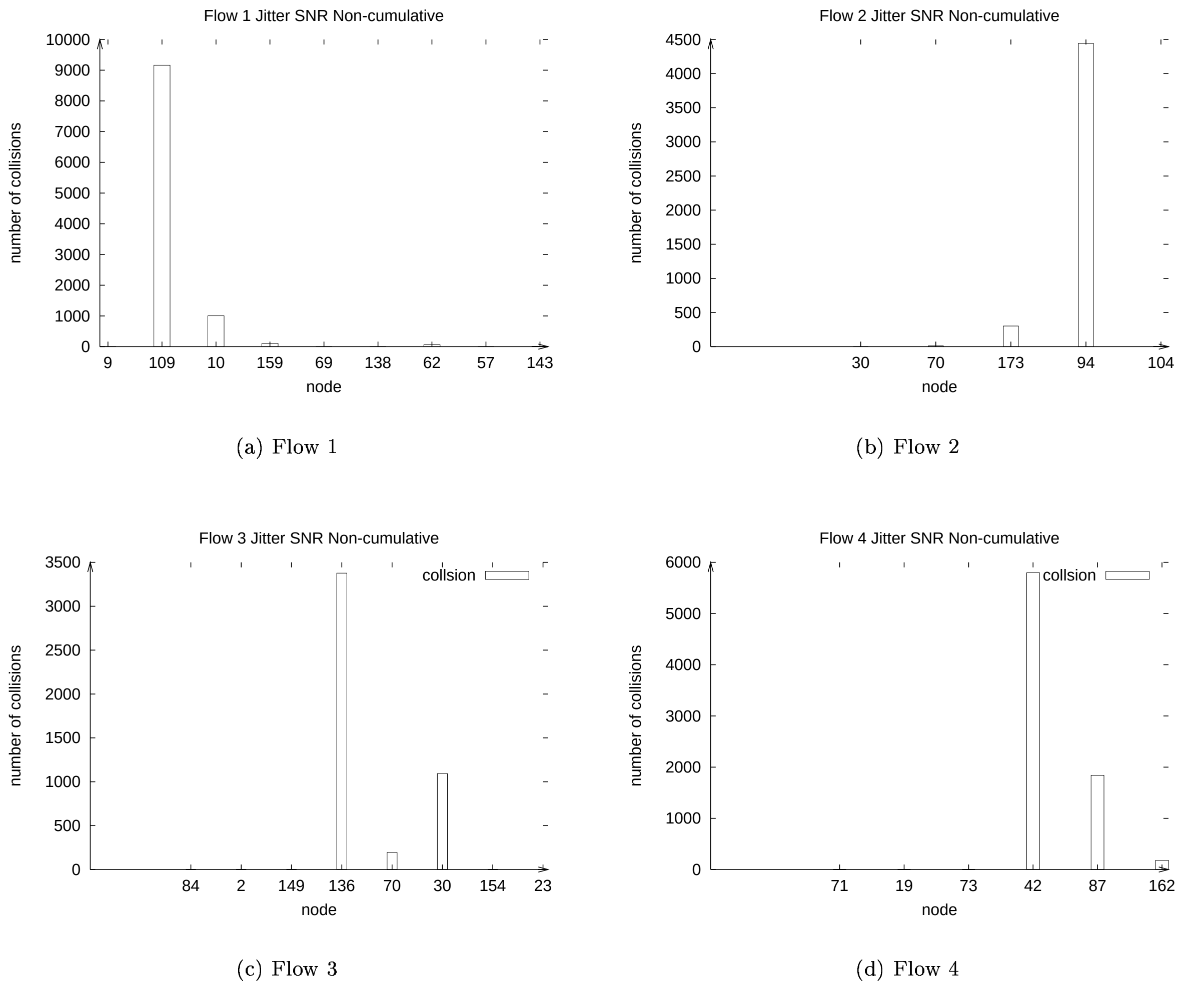
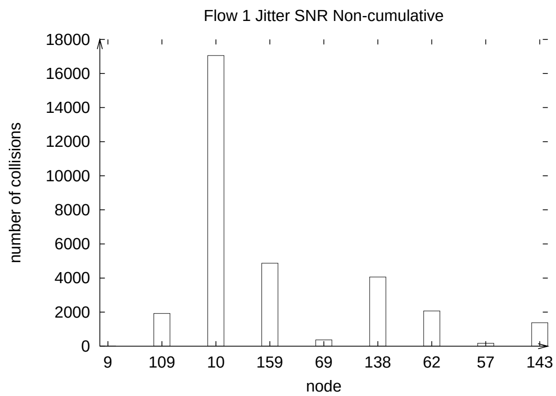
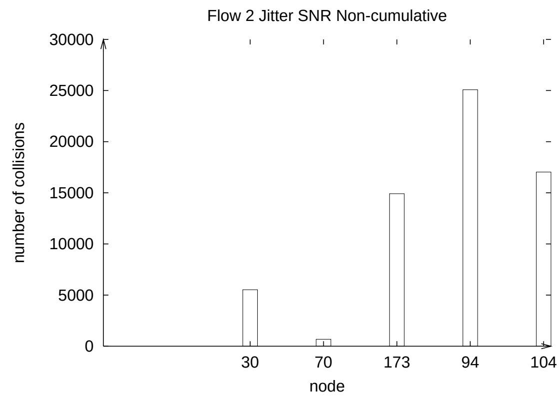


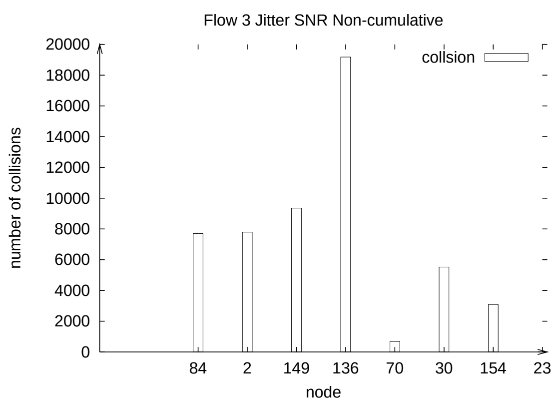
Figure 24: Total number of CBR packets from previous dropped due to collisions at the nodes of the 4 flows, with no jitter and cumulative SIR Model



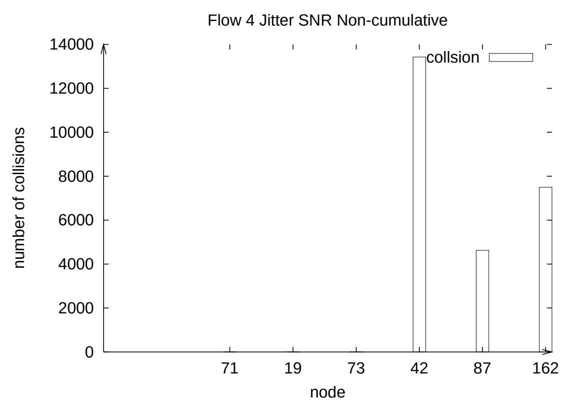
(a) Flow 1



(b) Flow 2

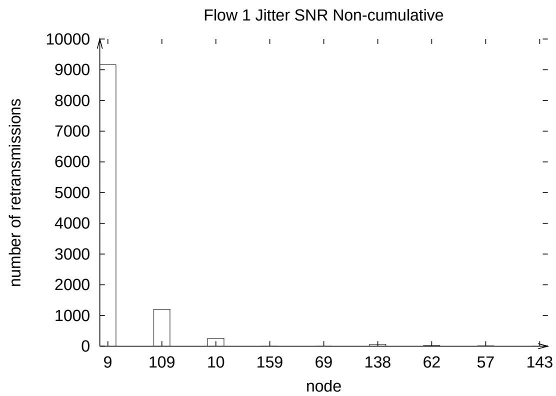


(c) Flow 3

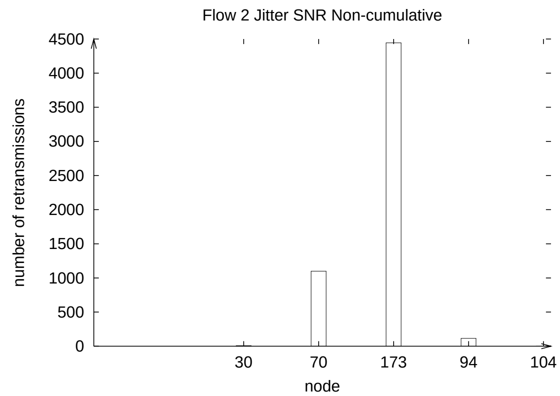


(d) Flow 4

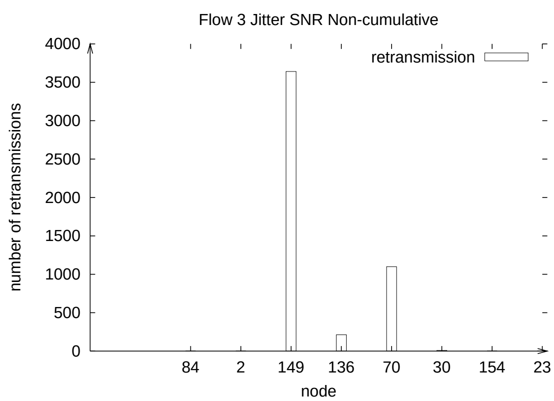
Figure 25: Total number of ACK packets destined to itself dropped due to collisions at the nodes of the 4 flows, with no jitter and cumulative SIR Model



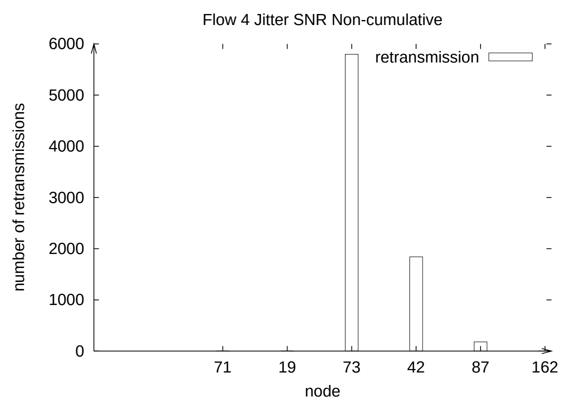
(a) Flow 1



(b) Flow 2

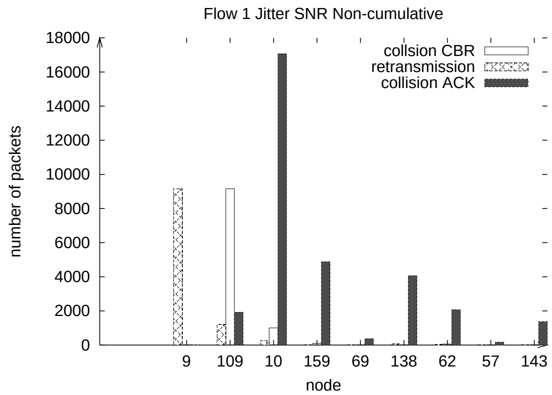


(c) Flow 3

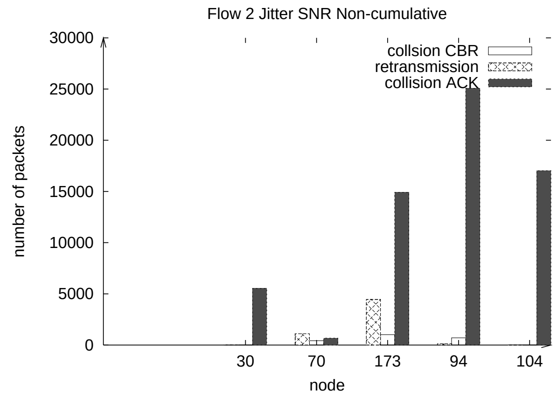


(d) Flow 4

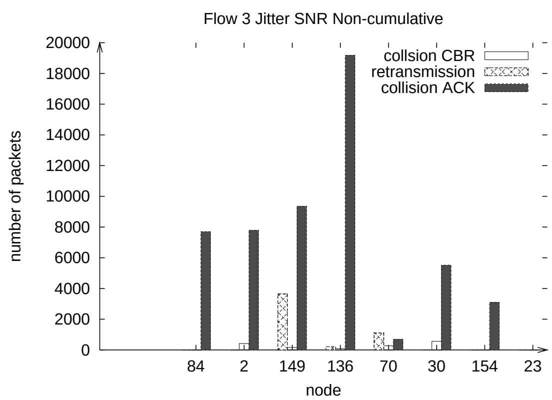
Figure 26: Total number retransmission at the nodes of the 4 flows, with no jitter and cumulative SIR Model



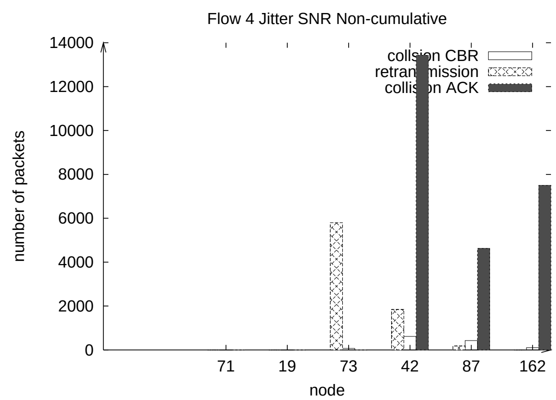
(a) Flow 1



(b) Flow 2



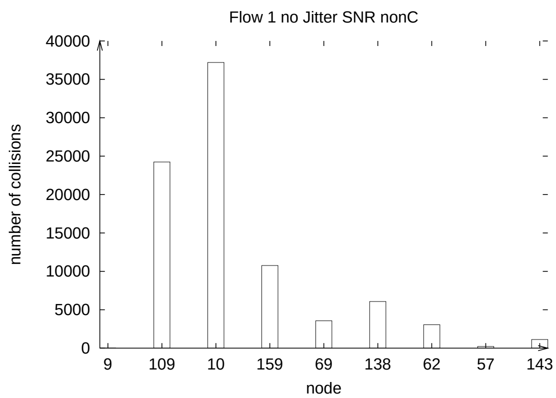
(c) Flow 3



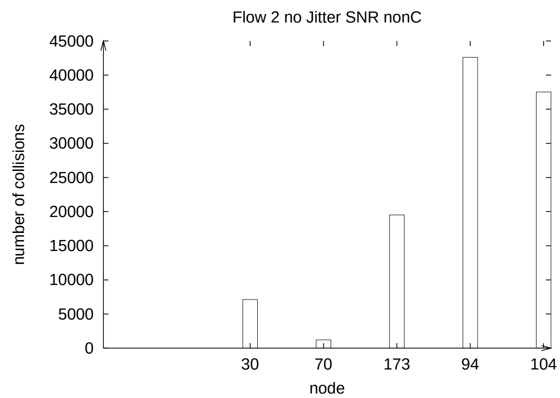
(d) Flow 4

Figure 27: Number of packets that caused extra energy consumption (due to collisions and retransmissions) at the nodes of the 4 flows, with no jitter and cumulative SIR Model

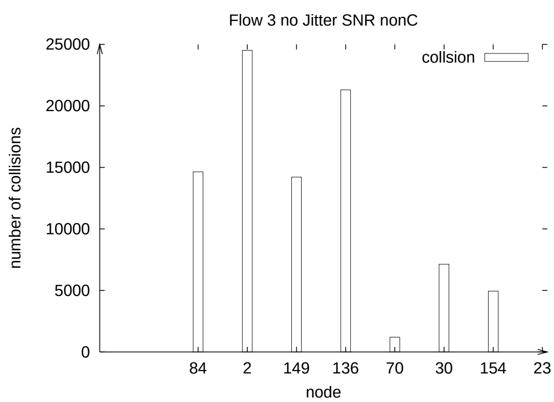
Results of the 4 flows, 200 nodes case, with no jitter and non-cumulative SIR Model



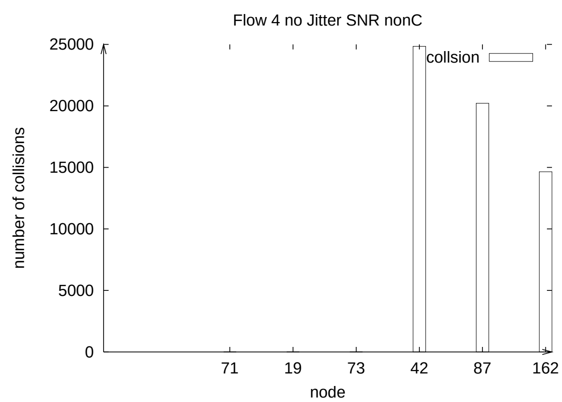
(a) Flow 1



(b) Flow 2

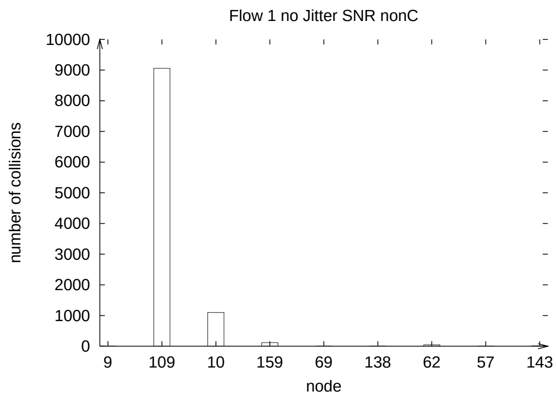


(c) Flow 3

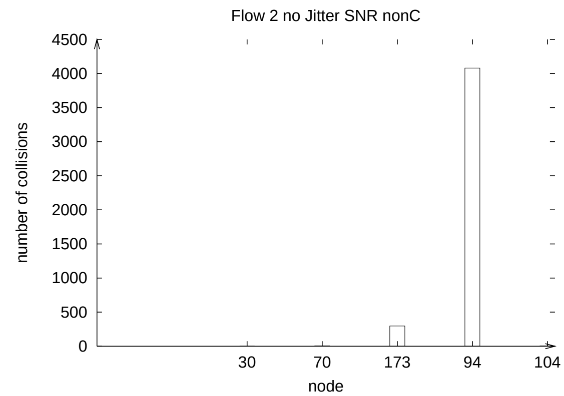


(d) Flow 4

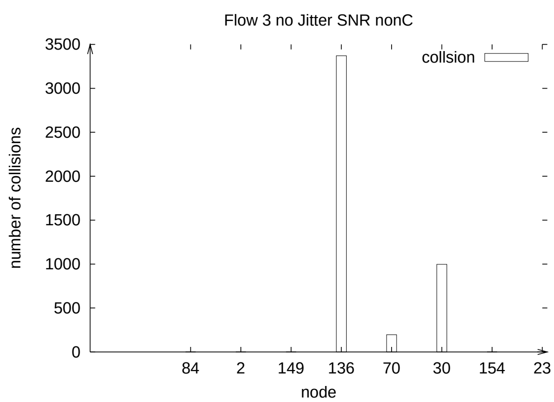
Figure 28: Total collisions at the nodes of the 4 flows, with no jitter and non-cumulative SIR Model



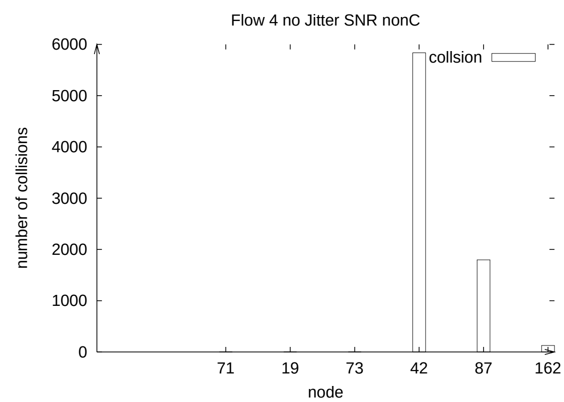
(a) Flow 1



(b) Flow 2

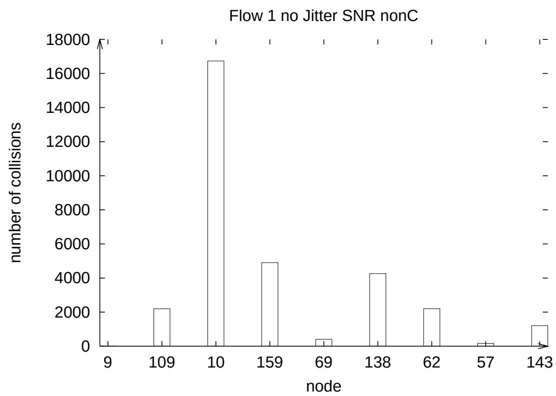


(c) Flow 3

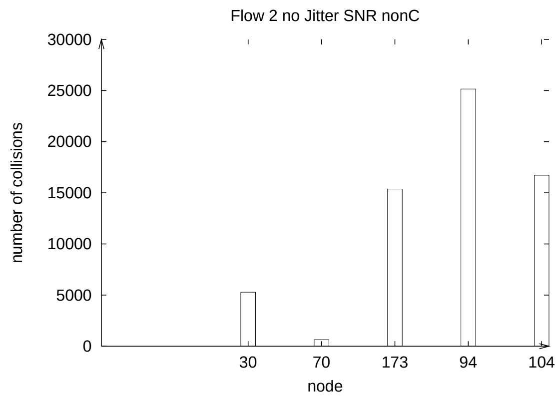


(d) Flow 4

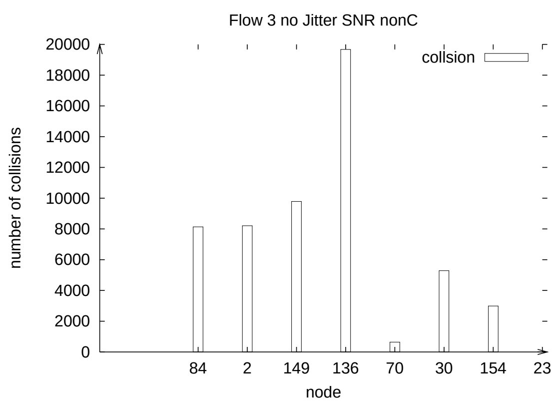
Figure 29: Total number of CBR packets from previous dropped due to collisions at the nodes of the 4 flows, with no jitter and non-cumulative SIR Model



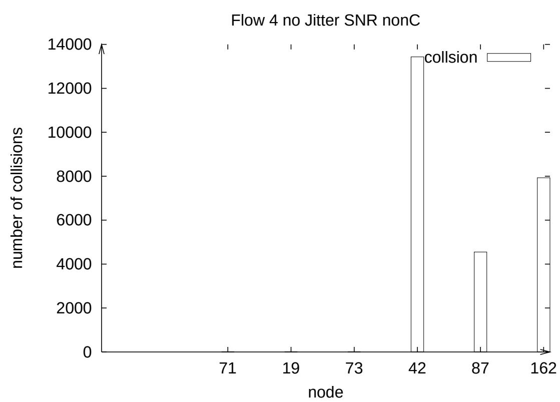
(a) Flow 1



(b) Flow 2

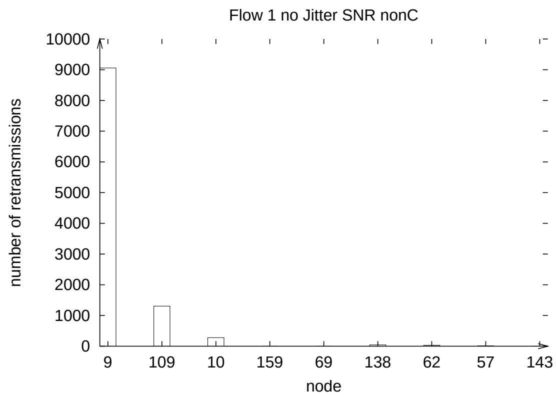


(c) Flow 3

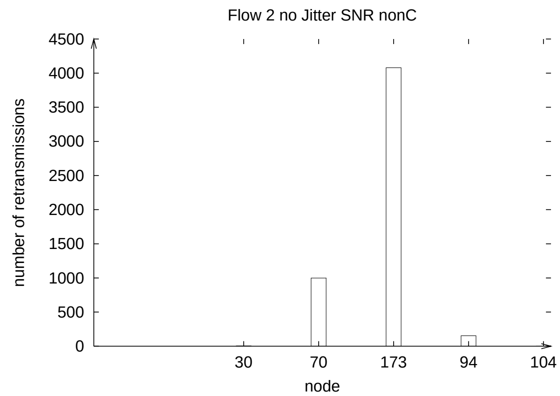


(d) Flow 4

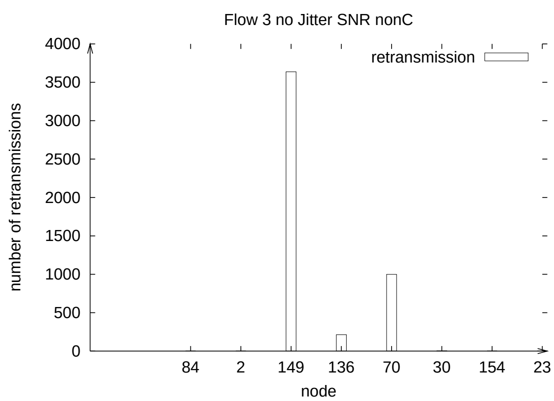
Figure 30: Total number of ACK packets destined to itself dropped due to collisions at the nodes of the 4 flows, with no jitter and non-cumulative SIR Model



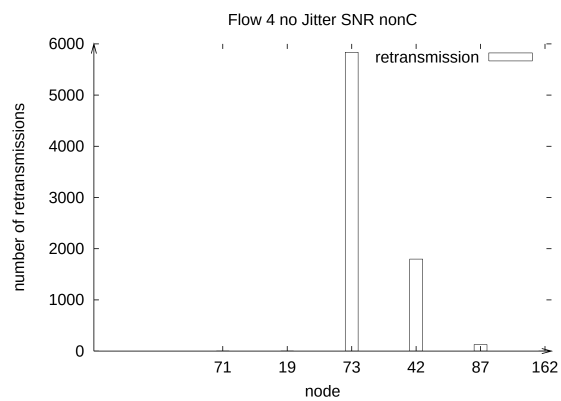
(a) Flow 1



(b) Flow 2

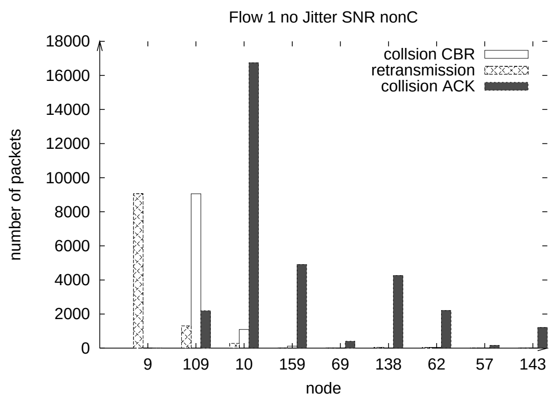


(c) Flow 3

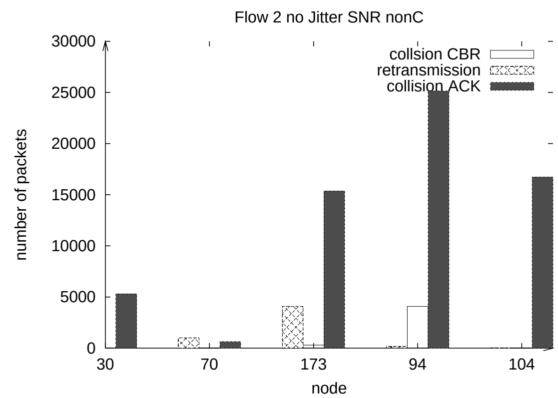


(d) Flow 4

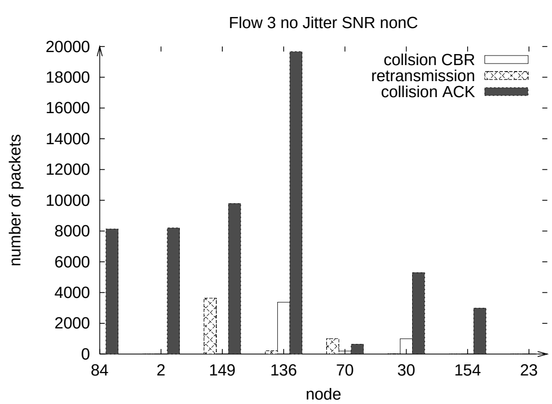
Figure 31: Total number retransmission at the nodes of the 4 flows, with no jitter and non-cumulative SIR Model



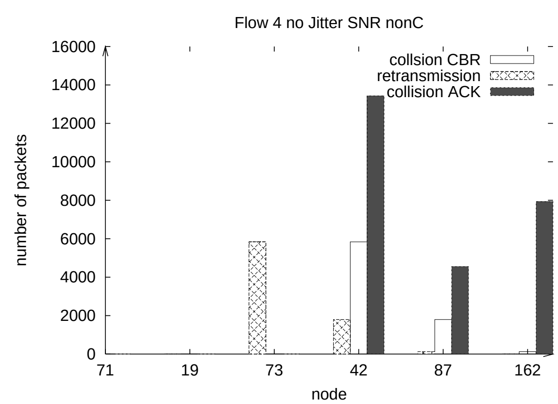
(a) Flow 1



(b) Flow 2



(c) Flow 3



(d) Flow 4

Figure 32: Number of packets that caused extra energy consumption (due to collisions and retransmissions) at the nodes of the 4 flows, without jitter and with non-cumulative SIR Model

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